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(57) Abstract

A microelectromechanical system (MEMS) optical switch is introduced which includes a mirror constructed on a substrate. The mirror is movable parallel to the surface of the substrate and either allows an input ray incident at an oblique angle, preferably 45°, to the mirror surface to pass undisturbed through a transparent part of a substrate or reflects the ray to an alternate output. Three embodiments of the switch are shown. The first includes a variation on a comb-drive designed to produce larger forces than usual by using an envelope-like electrode into which the mirror is drawn. Larger forces can be obtained by designing the electrode edges to have a long perimeter line, such as in a fractal form. A second implementation supports a mirror on flexible beams which are attracted or repelled by electrostatically charging curved electrodes thereby actuating the mirror. In a third implementation, a magnetic field around the switch induces lateral forces when electric current flows in conductive supporting beams to cause switching. Two-dimensional arrays of such switches are shown to be able to switch any of a set of input rays to any of a set of outputs. Three-dimensional arrays allow switching to be done with shorter ray paths and fewer mirrors than with other switches. Such a 3D implementation is presented. A wavelength separating and combining device is also introduced that splits a multi-wavelength beam into a bundle of parallel, single-wavelength rays. By reversing the operation of this device, the single-wavelength parallel beams can be recombined. Such a device, in combination with one of the presented switches, is useful in wavelength division multiplexing applications. Conventional methods are suggested for fabrication but, to enhance the quality of the mirrors and precision of their positioning and motion and speed of operation, it is proposed that they be fabricated on the surface of substrate wafers. An innovative method is presented in order to fabricate 2D and 3D arrays of these switches involving positioning of switch elements on wafers and stacking wafers vertically in a defined pattern.

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OPTO-MECHANICAL VALVE AND VALVE ARRAY

FOR FIBER-OPTIC COMMUNICATION

Field and Background of the Invention

The present invention relates to switching in optical networks such as optical communications networks and, more particularly, to an optomechanical valve and to arrays of optical valves generally and this valve in particular.

An essential component of any communications system is a switch to enable signal routing. Various types of devices are used for optical switching. Some transform the optical signal into the electrical domain, where switching is done and then retransform back to the optical domain. Others use integrated optics to perform switching, using materials such as lithium niobate. These devices are relatively expensive, their minimum size is limited by the physics of optical wave-guides, they are strongly dependent on wavelength, and they suffer from cross-talk and signal attenuation.

One way to overcome many of these limitations is to use mechanical optical switches (Motamedi M. E. *et al*, "Micro-opto-electro-mechanical devices and on-chip optical processing", *Optical Engineering* vol. 36 No. 5, May 1997, page 1282, and other articles in this issue of the journal). Micro-mechanical switches are not wavelength dependent and can be very compact. Signal loss occurs mainly at the input from and output into the fibers (which is about the same as for other switching technologies). Air accounts for only a very small portion of the attenuation. An N×N switch, that can route any of its N inputs to any of its N outputs, is simple to realize by an array of mirrors placed in the ray paths. By suitably actuating a mirror, or series of mirrors, a ray may be switched into any desired output path. There is no interference among the N inputs, since light-ray paths cross without interaction (Hecht J., "Optical switching promises cure for telecommunications log-jam", *Laser Focus World*, September 1998, page 69). There is thus almost no cross-talk between data lines.

The task is mainly the production of tiny mirrors to use as switches in these arrays. Micro-machined devices are capable of fulfilling the task, provided that the micro-machining produces optical-grade mirrors to reduce losses. Actuation needs to be fast, simple, and allow reproducible and accurate alignment of the beam inputs and outputs as the mirrors

bend the ray. In addition, the ability to deploy large arrays of mirrors is an essential feature of the system. All of these affect switching losses and utility. Previous art devices, although ingenious, were not able to achieve all of these requirements together. (See, for example: Toshiyoshi H. *et al*, "Electrostatic micro-torsion mirrors for an optical-switch matrix", *Journal of Microelectromechanical Systems*, vol. 5 No. 4, December 1996, page 231; and Marxer C. *et al*, "Vertical mirrors fabricated by deep reactive ion etching for fiber-optic switching applications", *Journal of Microelectromechanical Systems*, vol. 6 No. 3, September 1997, page 277.)

The valve and valve array of the present invention overcome the shortfalls of previous art.

Summary of the Invention

A microelectromechanical optical switch that transfers or reflects an input ray using a movable mirror constructed on the surface of a substrate and oriented at 45° to the ray's direction is presented. This switch is actuated parallel to the substrate's surface by electrostatic, magnetic, thermal, piezoelectric, or other means. In the case of electrostatic actuation, an envelope-style electrode may be used to obtain larger forces than are obtained in prior art configurations such as comb actuators, to produce faster switching. Designing the electrode edges to have a large perimeter or an irregular shape such as a fractal shape can increase this force even more. It should be noted that the terms "valve" and "switch" are used interchangeably herein.

Arrays of switches may switch rays from a plurality of inputs to any of a plurality of outputs. A three-dimensional switch array disclosed allows this switching to be done with shorter ray paths and fewer mirrors.

A wavelength separating and combining device that can separate a multi-wavelength beam into a bundle of parallel single-wavelength rays and recombine them is also disclosed.

Usual fabrication methods are employed but enhanced mirror alignment and performance are achieved by fabricating mirrors on the surface of a wafer. A novel method is disclosed for fabricating 2D and 3D arrays, by bonding several laterally displaced wafers on top of one another.

According to the present invention there is provided an optical switch for switching a light ray including: (a) a substantially planar substrate having a portion that is transparent to the light ray; (b) a switching element having at least one reflective surface substantially parallel to the substrate; and (c) a mechanism for moving the switching element in a direction parallel to the substrate between (i) a first position wherein the light ray traverses the transparent portion of the substrate to a first outlet and (ii) a second position wherein the light ray is blocked from traversing the transparent portion of the substrate and reflected by the reflective surface to a second outlet.

According to one embodiment of the present invention the mechanism moves the switching element substantially rectilinearly.

According to another embodiment of the present invention the mechanism moves the switching element substantially curvilinearly.

According to one embodiment of the present invention the substrate includes an opaque portion opposite which the switching element is located when in the first position and a transparent portion opposite which the switching element is located when in the second position.

According to another embodiment of the present invention the substrate includes a second transparent portion opposite which the switching element is located when in the first position.

According to the present invention there is provided a method for switching either of two light rays wherein: (a) the first ray is switched to an output while the second ray passes unswitched to another output when the switching element is in the first position and (b) the first ray passes unswitched to the latter output while the second ray is switched to the former output when the switching element is in the second position.

According to one embodiment of the present invention the mechanism includes shape memory alloys.

According to one embodiment of the present invention the mechanism is thermal.

According to another embodiment of the present invention the mechanism is piezoelectric.

According to another embodiment of the present invention the mechanism is electrostatic.

According to another embodiment of the present invention the mechanism is magnetic.

According to one embodiment of the present invention the electrostatic mechanism includes: (a) two planar electrodes serving as stators (i) parallel to the substrate, (ii) fixed to the substrate and insulated therefrom, (iii) having substantially equal shape and dimensions, and (iv) electrostatically chargeable, with same polarity; (b) a third, insulated, planar electrode that: (i) is movable in a plane parallel to and between the stators in a path such that the third electrode may be at rest in a first position substantially between the stators and in a second position substantially outside the stators, and (ii) is attached to the switching element; and (c) a mechanism for alternately charging the electrodes in: (i) a first charge configuration wherein a charge on the third electrode is of opposite polarity to a charge on the stators and (ii) a second charge configuration wherein a charge on the third electrode is of same polarity as a charge on the stators.

According to one embodiment of the present invention the stator edges wherebetween the path passes are straight.

According to another embodiment of the present invention these stator edges, and/or the leading edge of the third electrode, are circular.

According to another embodiment of the present invention these stator edges, and/or the leading edge of the third electrode, have an irregular form such as a fractal form.

According to another embodiment of the present invention the mechanism includes: (a) one or more stators, each of which: (i) is fixed to the substrate and insulated therefrom, (ii) has a circular segment shape, the circle lying in a plane parallel to a surface of the substrate, and (iii) is electrostatically chargeable; (b) at least one supporting beam for the switching element, each beam being: (i) flexible, (ii) attached at a point to the switching element and at another point to at least one of the stators, (iii) insulated from that stator, and (iv) electrostatically chargeable, and (c) a mechanism for alternately charging the stators and the beams in: (i) a first charge configuration wherein a charge on the beams is of opposite polarity to a charge on the stators and (ii) a second charge configuration wherein a charge on the beams is of same polarity as a charge on the stators.

According to another embodiment of the present invention the mechanism includes a beam attached at a center to the stator and at both ends thereof to the switching element.

According to another embodiment of the present invention the stators have a quadrant shape and each beam is attached at one end to a stator and at the other end to a switching element.

According to another embodiment of the present invention the stators include pairs of quadrant-shaped components separated by and tangential to the beam at the point of attachment thereto and so aligned that a radial boundary of each is collinear through that point of attachment.

According to another embodiment of the present invention the beams are bistable.

According to another embodiment of the present invention the mechanism includes: (a) a magnetic field perpendicular to the substrate; (b) one or more supporting beams for the switching element, each beam being: (i) flexible, (ii) bistable, (iii) attached at an end to the switching element and at another end to the substrate, and (iv) electrically conductive; and (c) a mechanism for causing an electric current to pass through the beams.

According to one embodiment of the present invention the magnetic field is produced by a permanent magnet.

According to another embodiment of the present invention the magnetic field is produced by an electro-magnet.

According to another embodiment of the present invention there is provided a two-dimensional matrix of optical switches, arranged in rows and columns wherein a switch is positioned at at least some intersections of each row with each column.

According to another embodiment of the present invention, each switch is oriented to be moveable in a direction of motion obliquely, preferably at an angle of 45°, to the rows and columns, and is actuatable independently of each other switch.

According to another embodiment of the present invention, each switch is oriented to be moveable in a direction of motion in and out of the plane defined by the rows and columns, and is actuatable independently of each other switch.

According to another embodiment of the present invention, an optical switches is positioned at each intersection of each row with each column.

According to another embodiment of the present invention there is provided a stationary reflective element located at a diagonal of this matrix in place of the switching elements there located and wherein switching elements are positioned only on a reflective side of the stationary reflective element.

According to the present invention there is provided a matrix of switches wherein at least one of the switches includes two reflective surfaces on opposite sides thereof.

According to the present invention there is provided a matrix of switches wherein at least one of the reflective surfaces of one of the switches is partly transmissive.

According to the present invention there is provided a three-dimensional switch array including a plurality of stacked, substantially identical, two-dimensional matrices of optical switches wherein each switch of one matrix is located opposite a corresponding switch of another matrix.

According to another embodiment of the present invention there is provided a three-dimensional switch array including a plurality of stacked, substantially identical, two-dimensional matrices of optical switches having a stationary reflective element at a diagonal wherein each switching element of one matrix is located opposite a corresponding switch of another matrix.

According to the present invention there is provided a three-dimensional switch array complex including a plurality of successive three-dimensional switch arrays wherein for each switch array except the first switch array: (a) an input face of that switch array faces and is parallel to an output face of a preceding switch array, (b) numbers of rows and columns of each succeeding switch array match numbers of columns and rows respectively of each preceding switch array, and (c) each succeeding switch array is oriented such that the rows and columns thereof are substantially aligned to the columns and rows of the preceding switch array.

According to the present invention there is provided a wavelength separator/recombiner including a first and second mutually parallel diffraction gratings, each including a plurality of diffractive elements on a surface thereof, the two gratings being offset so that a single input beam of light that includes a plurality of wavelengths and that is incident on the surface of one of the gratings, is diffracted by the gratings to produce one separate output beam of light for each wavelength with the separated beams being mutually parallel.

According to the present invention there is provided a method of demultiplexing a collimated wavelength-multiplexed beam and switching individual wavelength components to respective output ports, including the steps of: (a) directing the beam into the wavelength separator and (b) introducing the separated wavelength components into a switch array complex, and (c) switching the components to respective output ports thereof.

According to the present invention there is provided a method of multiplexing a plurality of individual wavelength rays into a single beam including the steps of: (a) introducing the individual wavelength rays into respective input ports of a three-dimensional switch array, (b) switching the rays, as required, to output ports of the array in a suitable alignment for introducing the rays into a wavelength recombiner for combining into a single multiplexed beam.

According to the present invention there is provided a method of fabricating the three-dimensional switch array including the steps of: (a) fabricating wafers containing independently actuatable optical switches arranged in equispaced rows and columns, the number of rows thereof being equal to the number of component two-dimensional switch matrices, (i) the first wafer having one column, and (ii) each succeeding wafer having one more column than a preceding wafer, until (iii) a last wafer having a number of columns equal to a number of input ports in each layer of the stack; (b) aligning the wafers with respect to one another such that: (i) the rows are all in parallel planes, (ii) the columns are parallel, and (iii) a group of columns in a succeeding wafer is centered opposite a group of columns in the preceding wafer; (c) bonding the aligned substrates together; and (d) dicing the bonded stack substantially parallel to the resulting square cross-section switch array and also substantially parallel to said columns.

According to another embodiment of the present invention there is provided a method of fabricating the three-dimensional switch array including further steps, beyond those of the preceding paragraph, of: (a) adding succeeding wafers, each said wafer, as before, containing independently actuatable optical switching elements arranged in equispaced rows and columns, the number of rows thereof being equal to the number of component two-dimensional switch matrices, and each succeeding wafer having one less column than a preceding wafer, and a final wafer having one column; (b) aligning the wafers with respect to one another such that: (i) the rows are all in parallel planes, (ii) the columns are parallel, and (iii) a group of columns in a succeeding wafer is centered opposite a group of columns in the preceding wafer; (c) bonding the aligned substrates together; and (d) dicing the bonded stack

substantially parallel to the resulting square cross-section switch array and also substantially parallel to said columns..

According to another embodiment of the present invention there is provided a method of including a planar static reflecting element located in place of the wafer with the largest number of columns, whereupon dicing is performed, parallel to the resulting rows and columns and also parallel to the static mirror and on a non-reflective side thereof.

Although the two-dimensional matrix of the present invention and the three-dimensional array of the present invention are described below in terms of the optical switch of the present invention, the scope of the present invention includes such matrices and arrays based on any kind of optical switch.

Brief Description of the Drawings

The invention is herein described, by way of example only, with reference to the accompanying drawings, wherein:

Figure 1 shows the general switch layout and basic switching motions;

Figure 2 shows switch zones;

Figure 3 shows basic switching actions;

Figure 4 illustrates how to obtain a switch that can direct two parallel inputs to separate outlets, by operating a switching element entirely within an optically active zone;

Figure 5 shows envelope actuation of a switching element;

Figure 6 presents two different possible designs for curved beam actuation;

Figure 7 illustrates the use of magnetic actuation;

Figure 8 shows some basic switching actions with two crossed rays;

Figure 9 presents a two variations of a basic switch array;

Description of the Preferred Embodiments

Introduction

The wave valve of the present invention is intended to be used in fiber-optic communications. It employs mirrors to perform the switching. Mirrors have the advantage of being substantially insensitive to wavelength. The active environment is a gas such as air, or a vacuum. This non-interfering environment allows ray paths to cross without interaction, so there is no cross-talk and almost no attenuation by the medium. Most of the losses occur during light transfer from and into the fiber at the switch/fiber interfaces. Losses are also introduced by spreading of the beam in space, but use of appropriate lenses and short distances can reduce these.

The mirrors should be small, to allow fast response, low losses, and compactness. The mirrors, in general, are micro-machined and, in order to reduce losses, are designed to be very smooth. They are generally planar and placed on a smooth wafer substrate, in contrast to previous art that etches the mirrors into the wafer bulk. In order to enhance switching speed, the mirror moves parallel to the substrate, thus reducing the influence of air resistance. This placement also minimizes small deviations of the mirror from the normal (90°) to the substrate that account for part of the losses introduced in prior art systems. The principles presented here are designed to give higher actuating forces, thus allowing a faster response than previous art.

Valve configuration and operation.

Referring to Figure 1a and 1b, the valve consists of a flat mirror, **1**, placed at a short distance, *d*, from and parallel to a substrate, **2**. Mirror **1** may move to different positions in a plane, **3**, parallel to a surface of substrate **2**, either substantially curvilinearly, as in the substantially circular, pendulum-like motion, **5** in Figure 1c or in a substantially rectilinear motion in any direction, such as **6** or **6A** in Figure 1d. In a preferred embodiment, motion is generally parallel or normal to a base line, **7** (Figure 2), that separates an opaque zone, **8**, of substrate **2**, wherethrough light **10** can not pass, from a transparent zone, **9**, wherethrough light **10** can pass and wherewithin switching takes place. Transparent zone **9** may be transparent because substrate **2** exists in zone **8** and is absent in zone **9**, or because the material of substrate **2** in zone **9** is transparent to the relevant wavelengths. Different embodiments of the principles disclosed here can be devised by those skilled in the art, in which it is possible to distinguish the zones in other ways.

One approach is illustrated in Figure 3. Mirror element **1** is located opposite an opaque zone, **38**, of substrate, **2**, while light, **10**, transits unobstructed through a transparent zone, **39**. In this condition, it is in an OFF state, **1A**, as shown in Figure 3a, b. Mirror **1** is movable rectilinearly, parallel to substrate **2**, into zone **39**, as shown by double-headed arrow **36**, to an ON state, **1B** (Figure 3c, d). While mirror **1** is in OFF state **1A**, light **10** can pass from one side, **39A**, of surface **3** to another side, **39B**, generally at an angle to said surface.

In a preferred embodiment (Figure 3e, f) ray **10** is inclined at 45° to mirror **1**. In OFF state **1A**, ray **10** transits the switching zone unimpeded from **10A** to **10B**. When mirror **1** is in ON state **1B**, light is reflected along an alternate path **10C**. Thus ray **10** has one input state, **10A**, and two possible, mutually exclusive, output states, **10B** and **10C**.

In another possible embodiment (Figure 4), mirror 1 is movable along a line of motion **46**, which lies entirely opposite a transparent part, **49**, of plane 3, and, by so doing, can simultaneously create obstructing and non-obstructing states in different parts of zone **49**. Mirror suspension and actuation elements are placed opposite another, opaque zone, **48**, of plane 3. As previously explained, in non-obstructing state **41A** (Figure 4c), light **10A** passes to exit **10B** while, in blocking state **41B**, light is reflected to an alternate output **10C**. In this configuration, where mirror **1** is entirely opposite transparent zone **49**, either position of mirror **1** can be designated as ON or OFF (Figure 4e, f). Thus, it is possible to have a valve with two parallel inputs, **10 IA** and **10 IIA**, being in an ON state for the former, reflecting ray

10 IA to output **10 IC**, while being in an OFF state for the latter, which passes to output **10 IIB** (Figure 4e). On actuating switch **1**, these states reverse and input ray **10 IA** is in an OFF state transiting to output **10 IB**, while input ray **10 IIA** is in an ON state, reflecting to output **10 IIC**. This makes a (1×2)×2 exchange switch, which may be used, for example, in a Banyan network.

More elaborate applications can be realized by combining two or more switching elements. It is important to note that the rays can traverse the switch in the reverse direction. In this case, inputs interchange with outputs and the switching options, explained above, are reversed.

Actuation

The valve consists of mirror **1** which is movable parallel to surface **3** and may be in at least two rest positions. Mirror **1** reflects light at one position and allows its passage at the other. A number of methods of actuating the valve are possible: thermal, magnetic, piezoelectric, mechanical, electrostatic actuation and actuation methods that rely on shape memory alloys are a few of many actuation methods known in the art.

Electrostatic envelope actuation

A preferred embodiment uses electrostatic actuation. Different schemes of electrostatic actuation can be used, among them a comb-drive mechanism. (Hirano T. *et al*, "Design, Fabrication, and operation of submicron-gap comb-drive microactuators", *Journal of Microelectromechanical Systems*, vol. 1 No. 1, March 1992, page 52.) In conventional comb-drive actuation, the actuation force depends on the change of the overlapping area between the driver's fingers and comb. Since usual fabrication methods limit that area to a small value, a large number of fingers is necessary to produce the required force. Therefore this kind of actuation is generally slow and requires large actuators. A different approach to this actuation principle is disclosed here (Figure 5).

Overlapping finger **51** and comb **52** form a capacitor (Figure 5b). The attractive force between the movable and static fingers is:

$$F = -\frac{\partial U}{\partial x}$$

where

$$U = \tfrac{1}{2} CV^2$$

is the electrical energy stored in the capacitor of capacitance C. The capacitance of a parallel-plate capacitor is determined by the geometric parameters thereof and depends linearly on the area (A) and inversely on the gap between the electrodes (g_0). In the case considered here:

$$C = \varepsilon_0 \frac{A}{g_0} = \varepsilon_0 \frac{h_0 x}{g_0}$$

The force is, therefore:

$$F = -\frac{\varepsilon_0 V^2 h_0}{2g_0}.$$

Where, ε_0 is the permittivity of the vacuum, V an electrical potential **53**, h_0 is width of the finger, x is the overlapping length of the finger in the direction of advance thereof, and g_0 is the gap between the moving finger and the static fingers. It is seen that the force is inversely proportional to the gap between the fingers and proportional to the width of the fingers. It does not depend on the thickness or the amount of overlap between moving and static fingers. Based on this conclusion, in order to achieve more force and thus faster switching speed, a configuration is disclosed in which the width of the finger is increased.

The production of wide fingers is generally difficult with conventional previous art. A fabrication method is disclosed in which the manufacture of wider fingers is easily done. Thus, fewer fingers, or even a single finger, can achieve sufficient force and thus faster switching times of the order of microseconds, compared to milliseconds with previous art. The disclosed actuator has an envelope-like configuration in which mirror / finger (moving electrode) **51** may enter or exit envelope (static actuating electrode) **52**.

In another embodiment (Figure 5**d**), at least two actuating electrodes are placed in a way that one set, **52A**, actuates to an ON position while the other, **52B**, **C**, actuates to an OFF position. Actuation can be made bistable: if the actuated mirror is supported by buckled beams a snap action to each position of the mirror results.

Another possible embodiment to implement bistability employs electrostatic snap (pull-in) action. The actuated element is attracted and adhered to an electrical isolated electrode at the end of its motion.

From the equations above, force exerted is given by:

$$F = -\frac{\varepsilon_0 V^2}{2g_0}\frac{\partial A}{\partial x}.$$

Since force depends on the change of area A with displacement x, the area change of this actuator should be enlarged, not only the width of the finger. Thus, for the actuator presented, the force can be enlarged further as follows: If the change in position is regarded as constant, ∂x, then it is possible to enlarge the attack-front perimeter (57, Figure 5c) the electrode crosses. In other words, the actuating electrodes entering line (**57**) should be enlarged. This line can be designed to be circular (**57B**, Figure 5e) instead of straight. This will enlarge the front from h_0 to $\frac{\pi h_0}{2}$ and the force increases correspondingly. Alternatively, or additionally, the leading edge of electrode **51** may be similarly enlarged.

Another embodiment increases the front length by using a high-perimeter geometrical form. Such a form can be an irregular form such as a fractal line designed for such application. The use of a fractal form can increase the actuating force by the ratio of its perimeter to the straight-line length.

Curved electrode actuation

Another electrostatic actuation method is presented in Figure 6, in which the post-fix **A** or **B** refers respectively to variant embodiments. One or more flexible beams, **67A** or **67B**, support a mirror, **61**. One point of the beam(s), **68A** or **68B**, is fixed in close proximity to a circular segment stator, **69A** or **69B**, attached to a substrate, **62**. These stators and beams are conductive and chargeable with opposite polarity. Beam **67A** or **67B** and stator **69A** or **69B**, respectively, are separated by insulators, **65A** or **65B**, from each other along the entire circular segment of stator **69A** or **69B** or, at least, at points where contact may occur, so as to prevent a short circuit (Figure 6a, b, c, and d).

Applying a potential difference between stator **69** and moving beam **67** provides charges of opposite polarities to stator **69** and beam **67**, so that the latter is attracted to the former, as close as permitted by the insulation (Figure 6b, 6d). Removing the potential difference allows beam **67** to return to its original shape. Since a free end of beam **67** is attached to mirror **61**, the consequent advance or retreat of the contact zone around the perimeter of stator **69** moves mirror **61** a distance L in a direction indicated by double-headed arrows **66A** and **66B**. This method is especially useful when actuating elements **67**, **68**, and **69** are

completely within substrate **62** with mirror **61** being entirely opposite transparent zone **63**, as described previously. It is a suitable alternative where envelope-type actuation is not preferred. Beams are produced curved so that actuation is inherently bistable. In order to move mirror **61** a distance **L**, the height of stator **69A** or **69B** should be **L**. If stator **69B** is a quadrant of a circle, the height should be the circle radius and have a value of **L**.

Another embodiment of this actuation method (Figure 6e, f) employs opposed-quadrant stators. In this case two quadrant-shaped stators, **69C**, are separated by one single beam, **67C**, so that beam **67C** is tangential to both quadrants at a point of contact and both quadrants are oriented so that a radial boundary of each quadrant forms a straight line passing through the point of contact. As before, both stators are separated from beam **67C** by insulating material, **65C**. In this configuration, by use of opposite charges on each member of a stator pair, half of the motion is effected by one member and the other half by the other member, in sequence. This allows a more compact actuator to be constructed.

Magnetic actuation

Another embodiment of the valve switch uses magnetic actuation. Magnetic fields can produce higher forces, and thus faster switching speed. The disadvantage is the larger overall volume of the device, even though the switching mechanism, itself, has the same dimensions whatever the actuation mechanism. In order to use this actuation method (Figure 7), a magnetic field, **B**, is necessary at the switch. The field can be produced by conducting loops around each switch; by a permanent magnet, larger than the switch; or by an electromagnet with similar field. These are only some of the available magnetic field application possibilities.

In this embodiment of the switch, mirror **71** is supported by beams, **77A** and **77B**. These beams are preferably made as curved beams, in order to allow bistable operation, and are conductive or include a conducting layer wherethrough an electric current, **I**, may be passed. Interaction with the magnetic field induces a lateral force, **F**, on the beams. Appropriate alignment of the magnetic field and the current actuates mirror **71** to a new position (Figure 7a). Reversing the current produces a reverse force that returns mirror **71** to an original position (Figure 7b). Higher field values or higher currents produce stronger forces and faster switching.

Valve Array

The single valve disclosed above is capable of switching light rays. Switching is possible between a single input and two outputs or two inputs into one output. The strength of the disclosed device, however, lies in its ability to switch many inputs to many outputs, within a compact space.

The disclosed switch can be incorporated into prior art optical devices (Figure 8). In order to switch one input to two outputs, one mirror, **82**, parallel to a substrate, **83**, as disclosed before, moves in a direction parallel to substrate **83**, as illustrated by double-headed arrow **84** (Figure 8a, b). If the switch is in an OFF state, an input ray, **81A**, emerges at output **81B**. If the switch is actuated to an ON state, ray **81A** reflects from mirror **82** and exits from output **81C**. Another embodiment can be designed (Figure 8c, d) wherein two inputs, **81A** and **81D**, are normal to each other and, in an OFF state, continue to respective outputs **81B** and **81C**. Actuating mirror **82** flips the output rays to emerge at interchanged outputs **81C** and **81B** respectively. In this latter embodiment, mirror **82** is reflective on both sides.

These are simple schemes, in which a single switching element is utilized. More elaborate examples can be produced by employing an array of switches (Figure 9a). (The fabrication of such an array is discussed below.) (It should be noted that the terms "array" and "matrix" are used interchangeably herein.) A column of inputs, **91A ... 91D**, is situated normal to a row of outputs, **92A ... 92D**, in the same plane. At an intersection of each input line with an output line, a switching mirror, **93** for example, is placed, at an oblique angle to the intersecting input line **91** and output line **92**. The preferred angle is 45°, as drawn. It is emphasized that each input can act as an output, and vice versa, by reversing the direction of ray propagation. In order to switch any input to any output, an appropriate switching mirror **93**, at an intersection of corresponding input and output axes is actuated to an ON state. The input is thus redirected to a desired output. For example, input **91B** may be directed to output **92D** by actuating switch **93A**. Since only a one-to-one correspondence is implemented (in the case that broadcast is not implemented), only a single switch is actuated at any time in each row and in each column. A non-blocking condition exists. When partly transmissive mirrors are used to allow broadcasting, "blocking" is allowed, in the sense that a light ray that enters the array along a row of switches may traverse two or more actuated switches, with a reflected ray being directed along the column of each actuated switch.

Another point should be emphasized. Although the inputs and outputs are generally normal to each other, more complicated switching operations, as basically described in Figs 8c and 8d, can be achieved by placing additional inputs, **94**, or outputs, **95**, outside the switching array, collinear with the original outputs and inputs respectively. In order to use these additional outputs (or inputs), as explained before, switches such as the switch illustrated in Figures 8c and 8d are used, and no switches should be actuated along the particular ray path concerned. All the switches of the respective input (or all the switches of the respective output, in the case of additional input) should not be actuated thus allowing unimpeded passage of the rays.

In Figure 9b, another embodiment is presented in which only half of an array is needed. In this case, a static reflecting element, such as a mirror **99**, as shown, or a waveguide termination, is placed at a diagonal of the array and that part of the array behind mirror **99** is discarded. (More elaborate effects may be obtained by placing, instead, actuatable mirrors at the array diagonal.) All actuatable mirrors are double sided. In this configuration, fewer actuatable elements are required to achieve desired output configurations, with the same ray path-length, although a ray may, thereby, encounter more reflecting surfaces, leading to greater light loss. Moreover, the overall switch is smaller, which is an advantage in some fabrication schemes, as will be shown below. In the example of Figure 9b, inputs **96A, B, C,** and **D,** are switched to outputs **97A, C, B,** and **D** respectively. Input **96A** is reflected to output **97A** *via* path α and input **96D** is reflected to output **97D** *via* path δ; it can be seen that these require no switching. Input **96B** is, however, switched to output **97C** *via* path β by reflecting at a back of actuated mirror **98.** At the same time, input **96C** is switched to output **97B** *via* path γ by reflecting at mirror **98.**

Although the embodiment shown has no broadcast possibility, this is not a restrictive example. Other embodiments can be devised wherein broadcasting is available. Such embodiments include mirrors that are partially reflective and partially transmissive. In such cases, more than one mirror is actuated, to produce broadcasting. Other schemes for broadcasting and multicasting can be designed by those skilled in the art, using the presented building blocks.

Most of the previous features of the array of switches are known from previous art and are applied to the specific embodiments disclosed here. In the case of small arrays, the number of switches is small and the short optical paths cause only small power losses. Some applications, however, require large numbers of inputs and outputs. For a 10x10 array, 100

switches are required. A 50 μm separation between switches will result in a longest path length of ~1 mm. For a 100x100 array, however, 10,000 mirrors are required and the longest path length is 1 cm. The large increase in dimensions and number of switches results in increased device losses.

A more elaborate switching device is now disclosed in which shorter paths and fewer switches are possible. The disclosed device enables this switching option. Other types of switches, both of the MEMS (microelectromechanical system) type, as is the switch of the present invention, and of other types (lithium niobate, liquid crystal, etc.), are also configurable in the arrays of the present invention, with MEMS switches being preferred.

An embodiment of this more elaborate device is presented schematically in Figure 10a. In an example of this embodiment, three switching arrays, **a**, **b**, and **c**, as described in Figure 9a or 9b, are utilized, the arrays being stacked, with corresponding elements vertically above one another. Each array operates either independently of the other arrays or in conjunction therewith. As will be seen below, the arrays are not merely stacked, but may be mutually coupled, to achieve more efficient switching, in a smaller volume, than is possible using prior art switch arrays.

Inputs, **101**, consist of stacked rows, denoted by **a**, **b**, **c** , and vertical columns denoted by **I**, **II**, **III**. Outputs, **102**, are similarly denoted. There is now a two-dimensional input array to a three-dimensional switch, leading to a two-dimensional output array. (The previously described device had a one-dimensional input array to a two-dimensional switch, leading to a one-dimensional output array.) Easy fabrication of this device is described below.

A realization of this arrangement is shown in Figure 10b, where a cut-away view of a two-layer array having four switching mirrors in each layer is shown, oriented similarly to the schematic view in Figure 10a. In this, inputs **103** may lead to outputs **104**. The upper layer has inputs **103 Ia** and **103 IIa** and outputs **104 Ia** and **104 IIa**, and switching mirrors **A1**, **A2**, **A3**, and **A4**; its possible light paths are illustrated by dotted lines. The lower layer has inputs **103 Ib** and **103 IIb** and outputs **104 Ib** and **104 IIb**, and switching mirrors **B1**, **B2**, **B3**, and **B4**; its possible light paths are illustrated by dashed lines. Not all light paths will be followed in any given instance. There is no interaction between the two layers.

The same Figure 10b can also illustrate the smallest realization of the half-array switch illustrated schematically in Figure 9b. In this case, mirrors **A1**, **A4**, **B1** and **B4** are fixed, mirrors **A3** and **B3** are absent, and mirrors **A2** and **B2** are actuable, as before, and also

reflective on both sides. Light paths beyond mirrors **A1**, **A4**, **B1** and **B4** will no longer be possible. As in the previous paragraph, there is no interaction between the two layers.

In a first 3D embodiment presented, there is no correlation between input rows. A basic use of this stack is connecting a number of inputs to outputs within a small space. The only advantage of this device is a saving of space. A more important use can, however, be envisioned for WDM (wavelength division multiplexing) networking wherein each plane is assigned to a different wavelength, there being a sufficient number of planes for the number of wavelengths, so that all inputs in each plane have the same wavelength. Previously separated wavelengths are conducted to the appropriate planes. For each wavelength, a 2D switching matrix routes inputs to desired outputs. These outputs are subsequently recombined for further transmission or other use.

Although inputs **101** and **103** and outputs **102** and **104** are illustrated in Figure 10 as being at right angles to each other, it will be appreciated that the switch array of the present invention may be configured with inputs and outputs at any convenient non-zero angle to each other.

Multi-layer switching

Another use of the 3D switching matrix shown in Figure 10 is in compact switching of a large number of inputs. The main purpose of this use is the reduction of a ray path-length and the number of switches necessary compared with a square switching array. Instead of using a 2D array with a 1D column of inputs and outputs, a 2D input matrix is utilized. Each plane, **a**, **b**, and **c**, consists of a non-blocking array. Such an array can be regarded as an operator that transforms the input row, **101 *Ia***, **101 *IIa***, **101 *IIIa***, at plane **a**, to output row, **102 *Ia***, **102 *IIa***, **102 *IIIa***, at plane **a**, and so on for the other planes. Since each plane is isolated from neighboring planes, the only possible operator action is to change the column index, ***I***, ***II***, ***III***, ..., between input and output.

This is not enough; what is required is the capability to switch any input array element to any output array element. The 3D operator of the preceding paragraph is able to change only the column index of each element in the input matrix. This can be overcome by a double application of the 3D operator wherein rows and columns at the output of the first stage are transposed into columns and rows at the input of the second stage. This second application of the operator will again change only the column index within each row of the second matrix, but this time the column indices are the former row indices. Thus, by applying the

3D operator represented by the 3D switching matrix twice in succession, with intermediate transposition, the necessary switching can be accomplished. Figure 11a illustrates the disposition of switching elements.

Practically, after rays transit a first switching matrix (**111**) emerging rays are introduced into a second similar switching matrix (**112**), rotated 90° with respect to matrix **111**. Matrix **112** may be switched differently from matrix **111**. A non-blocking switching can be achieved. A third switching matrix can be incorporated if the resulting overall switching is not sufficient for the application. In this case, the third matrix is rotated 90° with respect to matrix **112**. In this case, too, non-blocking states are obtained, but the non-blocking path that connects any given input to any given output may not be unique. As an example of the advantage gained by this design, consider the task of switching any or several of 100 inputs to any or several of 100 outputs (a 100x100 switch). To perform the task, three matrices are needed, with the second matrix rotated 90° with respect to the first matrix and with the third matrix rotated 90° with respect to the second matrix. Each switching matrix consists of a 10x10x10 cube, with 1000 switches. A total of 3000 switches are used. The longest optical path, for a switch separation of 50 μm, is $(10+10+10+10+10)\times 50$ μm = 2500 μm = 2.5 mm. This compares with 10,000 switches and a 1 cm optical path needed to perform the same task with a conventional 2D array.

In Figure 11b is illustrated an equivalent switch array complex using the 3D switching matrix of Figure 9b instead of that of Figure 9a, utilizing fixed mirrors along a diagonal of each matrix. In this case, a 100x100 switch requires only 1350 switches, not including the 100 fixed switches, along the diagonal.

As in the case of the two-dimensional matrix of Figure 9a, the three-dimensional arrays of Figures 10b and 11a can be configured with switches such as the switch illustrated in Figures 8c and 8d; providing the option of placing the arrays in switching states in which some or all input rays traverse the array without being reflected. In this case, too, special options, such as control, can be implemented. A 3D matrix need not be cubic and the input array may be, for example 10x10, 10x3, etc., provided that the second, rotated 3D matrix has a matching number of rows and columns. For a six-input matrix, arranged as a 3×2 array, two planes of 3×3 arrays are needed. The second cube then needs three planes of 2×2 arrays.

Based on the elements presented, those skilled in the art may find other variations covered by this invention. One possible variation is to alter the number of cubes used, applying one, two, three, four, *etc.*, cubes as required.

Wavelength de-multiplexing

Another embodiment includes the addition of a wavelength demultiplexing/multiplexing system to the above methods for use of the disclosed switch in WDM (wavelength division multiplexing). In this embodiment, information is transmitted through optical fiber, encoded within a group of different wavelengths. A wavelength de-multiplexing and multiplexing device is necessary to separate the different wavelengths at the entrance to a switch array and, after processing or use, recombine these wavelengths. Rays introduced into the described switch are preferably parallel to one another. A device that can accomplish this is presented.

Several technologies for wavelength separation exist. Among them, the use of diffraction gratings is popular. The embodiment introduced below uses a diffraction grating to separate the wavelengths into parallel rays that can be introduced into a 3D switch. A similar device receives and recombines the output bundle of parallel rays for insertion into a fiber.

The device used (Figure 12) includes two parallel reflective diffraction gratings, **121** and **122**, each with respective diffractive elements such as parallel rulings **124** or **125** on surfaces **126**, **127** that face each other. The distance between the separated wavelength rays is determined by parameters including the distance $\boldsymbol{d}$ between parallel diffraction gratings **121** and **122** and the spacing of parallel rulings **124**, **125**.

A collimated input beam, **123**, emerging from a fiber, is incident on a surface **126** of a first diffraction grating, **121**, at a predetermined angle, α. A simple mirror would reflect this beam at the same angle with respect to a normal to the surface of the mirror. A grating, however, diffracts different wavelengths (λ_1, λ_2, λ_3, ...) at different angles (β_1, β_2, β_3, ...); the sum of incident angle plus angle of diffraction is a function of wavelength. From this, it is clear that different wavelengths will be separated into different angles at diffraction grating **121**.

Since the relation between the input and output angles is the same for second diffraction grating **122** as for first diffraction grating **121**, and since the diffraction gratings are parallel,

the reflected angle from second diffraction grating **122** is equal to the angle of incidence, α, at first diffraction grating **121**. Since this angle α is equal for all wavelengths, rays of all wavelengths emerge parallel, displaced from one another, and at angle α, after reflecting from second diffraction-grating **122**. With this configuration, wavelengths are separated into parallel rays, with displacement depending upon inter-reflection-grating distance ***d***, incident angle α, and the spacings of rulings **124** and **125**.

Since the ray paths are reversible, reversing direction provides a device capable of recombining wavelengths before insertion into a fiber on output. The use of one device at an input to the matrix and a reversed one at an output allows de-multiplexing, switching, and multiplexing signals in a WDM network.

Fabrication

The three-dimensional arrays of the present invention may be fabricated using prior art technologies, albeit at a cost that may be uneconomical or impractical. Therefore, the scope of the present invention includes an innovative method of fabricating these arrays. The basic device is fabricated on top of a wafer surface, in contrast to previous art, where the mirrors may be etched into the substrate. The mirrors, which require substantially perfect surface quality, flatness, and parallelism, take advantage of high-quality substrates prepared for the microelectronics industry. Substrates of various dimensions, thicknesses, materials, and surface preparations are available.

Generally, the device can be prepared on any kind of material and the fabrication procedure is independent of substrate material. While the substrate material has no effect on the switches, apart from surface preparation and physical dimensions, it is possible to take advantage of the substrate's properties. For example, electronic circuitry may be integrated into the substrate or optical fibers may be set therein, in which case advantage can be taken of features such as the crystallographic planes of the substrate material, as in silicon. Those skilled in the art may find different materials and techniques for the production of these switches.

Single-switch fabrication

Fabrication starts with a substrate, **132** (Figure 13). Mirror material, **131**, generally a metal such as aluminum, is deposited on substrate **132** and patterned using standard methods such

as lithography. Generally, mirror **131** is produced on top of substrate **132** at a zone, **133**, where substrate material eventually will be absent so that a ray may pass through (Figure 13b).

In another fabrication procedure (Figure 13c, d), mirror **131** is fabricated above a portion of substrate **132** where substrate material eventually will be present. In this case a sacrificial layer, **134**, is deposited on top of substrate **132**; patterned, if necessary, to allow the deposition of subsequent layers that must penetrate through sacrificial layer **134** to reach substrate **132**; and polished prior to deposition and patterning of mirror **131**. Along with mirror **131**, supporting beams **135** are deposited and patterned above sacrificial layer **134**. Supporting beams **135** can be made of any material; in many cases they are made of metal or are otherwise conductive. Supporting beams **135** are fabricated attached to mirror **131** and substrate **132**. The number and configuration of supporting beams **135** depend on the application.

After deposition and patterning of the mirror **131** and supporting beams **135**, these moving elements are released by dissolving sacrificial layer **134** (Figure 13d) or by etching away substrate **132** under mirror **131** (Figure 13b). These procedures free mirror **131** and beams **135**. Further fabrication steps depend on the actuation mechanism.

Fabrication of electrodes and conducting lines can be done together, before or after the above-mentioned steps.

In case of envelope/comb actuation (Figure 13e, f), an electrode, **136**, is deposited on substrate **132** and covered by a sacrificial layer (**134**). The above-mentioned steps for fabrication of mirror **131** are carried out on top thereof. A second electrode of the envelope can be produced in a few ways. In one way (Figure 13e, f) mirror **131** is covered by a second sacrificial layer, **134A**. Second layer **134A** is patterned and covered by a second envelope electrode, **137**, which is patterned. By removing the sacrificial layers, the envelope is formed and mirror **131** is released.

Another possibility is depositing and patterning a second envelope electrode **137** on another side of substrate **132** or, as illustrated in Figure 13g, on another substrate, **132A**. By aligning and bringing together a mirror side of substrate **132** and a second-electrode side of substrate **132A**, and bonding, an envelope is formed (Figure 13h). Bonding is done by one of the known wafer-bonding methods, such as fusion bonding. Spacers and electrical connection paths are deposited and patterned as required prior to alignment and bonding.

In the case of curved electrode actuation, the mirror can be processed directly on a wafer surface at a ray traverse zone. Supporting beams are deposited and patterned on top of the mirror, as previously explained. It is possible to deposit material for the static curved electrode and to do the patterning simultaneously, followed by insulation deposition and patterning over the static electrode. Etching the sacrificial layer and corresponding substrate area releases the movable elements.

In the case of magnetic actuation, the supporting beams may act also as conducting lines, and there is no need for further fabrication steps. The mirror and beams are fabricated and released.

Other methods for single-switch fabrication can be devised by those skilled in the art. It is emphasized, however, that the choice of fabrication method on the substrate surface is advantageous to obtaining good quality mirrors and acquiring better control over alignment of the mirrors.

Switch array fabrication

The construction of a switch array requires more elaborate methods than single-switch fabrication. The disclosed method is designed to facilitate accurate construction of a 3D cubic array.

In order to simplify understanding of the fabrication method, a 4×4×4 array is described (Figure 14). This is only an illustrative example and does not limit the applicability of the method.

Single switches, **141,** are produced, as described previously, in rows, **143,** on a surface, **142,** of a substrate. In our example, there are four rows. These switches are also arranged in groups, **145,** of regularly spaced columns, **144,** each group being separated from a neighboring group by an empty column, **146,** at the same column spacing. The first group of our example consists of one column of four rows, separated by an empty column from a second group consisting of two columns of four rows followed by another empty column. The arrangement continues with successive groups of 3×4 and 4×4 to form a set. An entire wafer may be covered with such sets. For our example, at least seven such sets are required.

In order to fabricate a box array, these sets are carefully aligned, each on top of another, and bonded. A first set is placed at the bottom ready for an alignment (Figure 14b). A second

wafer is aligned on top of and parallel to the first, with a second group of columns (2×4) centered above a single-column group of the first wafer. This alignment is obtained by suitably displacing the second wafer with respect to the first, in a direction parallel to rows **143**. This procedure is continued with consecutive wafers, a 3×4 group of columns being centered above the 2×3 group, and a 4×4 group being centered above the 3×4. Stacking is then continued in a reverse order, a 3×4 group being centered above the 4×4 group, and so on, until a 1×4 group is placed on top of a second 2×4 group. The stack is then bonded. Viewed from the side, it is seen that the mirrors form a 2D matrix having column, **147**, and row, **148**, directions oriented at 45° to the surfaces of substrates **142**. The mirrors are oriented at 45° to these column and row directions. In this example, the array is four deep.

If the configuration shown in Figure 9b is fabricated, only half of the above array is required. One set of switching mirrors, at a reflecting middle plain, **149**, is replaced by a plain static mirror substrate and the mirrors on the non-reflective side of plain **149** are not required.

After bonding is completed, accurate dicing is performed, preferably parallel to columns **147** and rows **148** of the mirror array, along the lines **140**. A cubic array of mirrors results. This array is further packaged by aligning with input and output fibers. It is also possible to align two or more such cubes and to rotate one with respect to the other so that a 3D-switching device, as explained before, is produced.

Similar steps are followed to produce arrays of other dimensions, including rectangular arrays that are not square.

Operation

These switches are actuated by one of the previously specified methods through conducting lines which connect rows, columns, and planes, as appropriate. By applying an appropriate voltage or current to a particular mirror, that mirror may be set or reset into an ON or Off position.

It is readily apparent, in Figure 14, that these switches may be actuated by moving their mirrors in one of two orthogonal directions: a first direction, in the planes defined by columns **147** and rows **148**, at 45° angles to columns **147** and rows **148** (left-right in the plane of Figure 14); and a second direction, in and out of the planes defined by columns **147** and

rows **148** (in and out of the plane of Figure 14); or in a linear combination of these two orthogonal directions.

Applications

The switch presented can be used for switching input rays of different wavelengths from numerous input paths to numerous output paths. It is primarily intended for use in communications. Together with the wavelength separation and re-combination device disclosed above, it is applicable to WDM. Other applications, such as in optical computation, *etc.*, will be evident.

While the invention has been described with respect to a limited number of embodiments, it will be appreciated that many variations, modifications and other applications of the invention may be made.

What is Claimed Is:

1. An optical switch for switching a light ray comprising:
   (a) a substantially planar substrate having a portion that is transparent to the light ray;
   (b) a switching element having at least one reflective surface substantially parallel to said substrate; and
   (c) a mechanism for moving said switching element in a direction parallel to said substrate between
      (i) a first position wherein said light ray traverses said transparent portion of said substrate and
      (ii) a second position wherein said light ray is blocked from traversing said transparent portion of said substrate and reflected by said reflective surface.

2. The system of claim 1 wherein said mechanism moves said switching element substantially rectilinearly.

3. The system of claim 1 wherein said mechanism moves said switching element substantially curvilinearly.

4. The system of claim 1 wherein said substrate includes an opaque portion and wherein said switching element is opposite said opaque portion when in said first position and opposite said transparent portion when in said second position.

5. The system of claim 4 wherein said substrate includes a second transparent portion and wherein said switching element is opposite said second transparent portion when in said first position.

6. The system of claim 1 wherein said mechanism includes shape memory alloys.

7. The system of claim 1 wherein said mechanism is thermal.

8. The system of claim 1 wherein said mechanism is piezoelectric.

9. The system of claim 1 wherein said mechanism is electrostatic.

10. The system of claim 1 wherein said mechanism is magnetic.

11. The system of claim 9 wherein said mechanism includes:

    (a) two planar electrodes serving as stators:

        (i) parallel to said substrate ,

        (ii) fixed to said substrate,

        (iii) having substantially equal shape and dimensions, and

        (iv) electrostatically chargeable, with same polarity;

    (b) a third, insulated, planar electrode:

        (i) movable in a plane parallel to and between said stators in a path such that said third electrode may be at rest in a first position substantially between said stators and in a second position substantially outside said stators, and

        (ii) attached to said switching element; and

    c) a mechanism for alternately charging said electrodes in:

        (i) a first charge configuration wherein a charge on said third electrode is of opposite polarity to a charge on said stators and

        (ii) a second charge configuration wherein a charge on said third electrode is of a same polarity as a charge on said stators.

12. The system of claim 11, wherein said stators are insulated from said substrate.

13. The system of claim 11 wherein edges of said stator wherebetween said path passes are straight.

14. The system of claim 11, wherein at least one edge of at least one of said electrodes is circular.

15. The system of claim 11, wherein at least one edge of at least one of said electrodes has an irregular form.

16. The system of claim 15, wherein said irregular form is a fractal form.

17. The system of claim 9 wherein said mechanism includes:

(a) at least one stator, each of which:

(i) is fixed to said substrate and insulated therefrom,

(ii) has a circular segment shape, said circle lying in a plane parallel to a surface of said substrate, and

(iii) is electrostatically chargeable;

(b) at least one supporting beam for said switching element, each of said at least one supporting beam being:

(i) flexible,

(ii) attached at a point to said switching element and at another point to at least one of said stators,

(iii) insulated from said at least one stator, and

(iv) electrostatically chargeable; and

(c) a mechanism for alternately charging said stators and said beams in:

(i) a first charge configuration wherein a charge on said beams is of opposite polarity to a charge on said stators and

(ii) a second charge configuration wherein a charge on said beams is of same polarity as a charge on said stators.

18. The system of claim 17 wherein at least one of said beams is attached at a center thereof to a respective said stator and at both ends thereof to said switching element.

19. The system of claim 17 wherein:

(a) said stators have a quadrant shape and

(b) each of said beams is attached at an end thereof to a respective said stator and at another end thereof to said switching element.

20. The system of claim 19 wherein said stators include pairs of quadrant-shaped components separated by and tangential to said beam and so aligned that a radial boundary of each said stator is collinear through said point of attachment of said stator to said beam.

21. The system of claim 19 wherein said beams are bistable.

22. The system of claim 10 wherein said mechanism includes:

    (a) a magnetic field perpendicular to said substrate;

    (b) at least one supporting beam for said switching element, each of said at least one supporting beam being:

        (i) flexible,

        (ii) bistable,

        (iii) attached at an end thereof to said switching element and at another end thereof to said substrate, and

        (iv) electrically conductive; and

    (c) a mechanism for causing an electric current to pass through said beams.

23. The system of claim 22 in which said magnetic field is produced by a permanent magnet.

24. The system of claim 22 in which said magnetic field is produced by an electro-magnet.

25. A two-dimensional matrix of optical switches of claim 1 arranged in rows and columns wherein one of said switches is positioned at each of at least some intersections of said rows with said columns.

26. The system of claim 25 wherein said switches are oriented such that said direction of motion of each said switch is at an oblique angle to said rows and columns, and said switches are actuatable independently of each other.

27. The system of claim 26, wherein said oblique angle is 45°.

28. The system of claim 26 further comprising at least one fixed reflecting element located at a diagonal of said matrix and wherein said switches are positioned only on a reflective side of said at least one fixed reflecting element.

29. The system of claim 25, wherein said switches are oriented such that said direction of motion is in and out of a plane of said rows and columns.

30. The system of claim 25 wherein one of said switches is positioned at each of said intersections.

31. The system of claim 30, wherein all of said switching elements include two said reflective surfaces on opposite sides thereof, so that:

(a) when all of said switches in one of said rows are open, a light ray incident on said row transits said row;

(b) when all of said switches in one of said columns are open, a light ray incident on said column transits said column; and

(c) when one of said switches, at said intersection of one of said rows and one of said columns, is closed, and all other switches of said row and said column are open, a light ray incident on said row exits said matrix via said column and a light ray incident on said column exits said matrix via said row.

32. The system of claim 25 wherein at least one of said switching elements includes two said reflective surfaces on opposite sides thereof.

33. The system of claim 25 wherein at least one of said reflective surfaces is partly transmissive.

34. A three-dimensional switch array comprising a plurality of stacked, substantially identical, two-dimensional matrices of optical switches of claim 28 wherein each switch of each said matrix is located opposite a corresponding switch of at least one other said matrix.

35. A three-dimensional switch array comprising a plurality of stacked, substantially identical, two-dimensional matrices of optical switches of claim 30 wherein each switch of each said matrix is located opposite a corresponding switch of at least one other said matrix.

36. A three-dimensional switch array complex comprising a plurality of successive switch arrays of claim 34 wherein, for each said switch array other than a first said switch array:

(a) an input face of said each switch array faces and is parallel to an output face of a preceding said switch array;

(b) numbers of rows and columns of said each switch array match numbers of columns and rows, respectively, of said preceding switch array; and

(c) said switch array is oriented such that said rows and columns thereof are substantially aligned to said columns and rows of said preceding switch array.

37. A three-dimensional switch array complex comprising a plurality of successive switch arrays of claim 35 wherein, for each said switch array other than a first said switch array:

(a) an input face of said each switch array faces and is parallel to an output face of a preceding said switch array;

(b) numbers of rows and columns of said each switch array match numbers of columns and rows respectively of said preceding switch array; and

(c) said switch array is oriented such that said rows and columns thereof are substantially aligned to said columns and rows of said preceding switch array.

38. A wavelength separator/combiner comprising:

(a) a first diffraction grating including a first plurality of diffractive elements on a surface thereof; and

(b) a second diffraction grating including a second plurality of diffractive elements on a surface thereof that is parallel to and offset from said surface of said first reflection grating;

so that a single beam of light, that includes a plurality of wavelengths and that is incident on said surface of said first diffraction grating, is diffracted by said diffraction gratings to produce a corresponding plurality of single wavelength beams of light.

39. A method of demultiplexing a collimated wavelength-multiplexed beam and switching individual wavelength components thereof to respective output ports, comprising the steps of:

(a) providing a wavelength separator/combiner including:

(i) a first diffraction grating including a first plurality of diffractive elements on a surface thereof, and

(ii) a second diffraction grating including a second plurality of diffractive elements on a surface thereof that is parallel to and offset from said surface of said first diffraction grating;

(b) directing the beam at said surface of said first diffraction grating, thereby separating the beam into the individual wavelength components ,

(c) introducing the components into the switch array complex of claim 34, and

(d) switching the components to respective output ports thereof.

40. A method of demultiplexing a collimated wavelength-multiplexed beam and switching individual wavelength components thereof to respective output ports, comprising the steps of:

(a) providing a wavelength separator/combiner including:

(i) a first diffraction grating including a first plurality of diffractive elements on a surface thereof, and

(ii) a second diffraction grating including a second plurality of diffractive elements on a surface thereof that is parallel to and offset from said surface of said first diffraction grating;

(b) directing the beam at said surface of said first diffraction grating, thereby separating the beam into the individual wavelength components ,

(c) introducing the components into the switch array complex of claim 35, and

(d) switching the components to respective output ports thereof.

41. A method of multiplexing a plurality of individual wavelength rays into a single beam comprising the steps of:

(a) providing a wavelength separator/combiner including:

(i) a first diffraction grating including a first plurality of diffractive elements on a surface thereof, and

(ii) a second reflection grating including a second plurality of diffractive elements on a surface thereof that is parallel to and offset from said surface of said first diffraction grating;

(b) introducing the individual wavelength rays into respective input ports of the switch array of claim 34;

(c) switching said rays, in a suitable alignment for combining said rays into a single multiplexed beam in said wavelength recombiner; and

(d) directing said rays, so aligned, at said surface of said first diffraction grating, thereby combining said rays into said single multiplexed beam.

42. A method of multiplexing a plurality of individual wavelength rays into a single beam comprising the steps of:

(a) providing a wavelength separator/combiner including:

(i) a first diffraction grating including a first plurality of diffractive elements on a surface thereof, and

(ii) a second diffraction grating including a second plurality of diffractive elements on a surface thereof that is parallel to and offset from said surface of said first diffraction grating;

(b) introducing the individual wavelength rays into respective input ports of the switch array of claim 35;

(c) switching said rays, in a suitable alignment for combining said rays into a single multiplexed beam in said wavelength recombiner; and

(d) directing said rays, so aligned, at said surface of said first diffraction grating, thereby combining said rays into said single multiplexed beam.

43. A method of fabricating a three-dimensional optical switch array comprising the steps of:

(a) fabricating a plurality of wafers containing the optical switches arranged in equispaced rows and columns, a number of rows thereof being equal to a number of said stacked matrices, with:

(i) a first said wafer comprising one said column, and

(ii) each succeeding wafer comprising one more said column than a preceding wafer thereof, until

(iii) a last said wafer having a number of columns equal to a number of input ports in each layer of said stack;

(b) aligning said wafers with respect to each other such that:

(i) said rows are all in parallel planes,

(ii) said columns are parallel, and

(iii) a group of said columns in a succeeding said wafer is centered opposite a group of said columns in a preceding said wafer; and

(c) bonding said aligned substrates together.

44. The method of claim 43, further comprising the step of:

(d) dicing said bonded stack.

45. The method of claim 43, wherein said dicing is substantially parallel to a resulting square cross-section switch array and also substantially parallel to said columns.

46. The method of claim 43, further comprising the steps of:

(d) adding succeeding said wafers, each said wafer having one less said column than a preceding wafer thereof, until a final wafer comprising one column;

(e) aligning said wafers with respect to each other such that:

(i) said rows are all in parallel planes,

(ii) said columns are parallel, and

(iii) a group of said columns in a succeeding said wafer is centered opposite a group of said columns in a preceding said wafer;

(f) bonding said aligned substrates together; and

(g) dicing said bonded stack.

47. The method of claim 46, wherein said dicing is substantially parallel to a resulting square cross-section switch array and also substantially parallel to said columns.

48. The method of claim 43, further comprising the steps of:

(e) substituting a planar static reflecting element for said wafer that has a largest said number of said columns.

49. In the system of claim 5, a method for switching either of only two light rays wherein:

(a) a first said ray is reflected to a first output when said switching element is in a first position, while a second said ray passes unswitched to a second output and

(b) said first ray passes unswitched to said second output when said switching element is in a second position, while said second ray is reflected to said first output.

50. A two-dimensional matrix of optical switches arranged in rows and columns wherein one of said switches is positioned at each of at least some intersections of said rows with said columns.

51. The matrix of claim 50 wherein one of said switches is positioned at each of said intersections.

52. A three-dimensional switch array comprising a plurality of stacked, substantially identical, two-dimensional matrices of optical switches of claim 50 wherein each switch of each said matrix is located opposite a corresponding switch of at least one other said matrix.

53. A three-dimensional switch array complex comprising a plurality of successive switch arrays of claim 52 wherein, for each said switch array other than a first said switch array:

(a) an input face of a said switch array faces and is parallel to an output face of a preceding said switch array,

(b) numbers of rows and columns of said each switch array match numbers of columns and rows respectively of said preceding switch array and

(c) said switch array is oriented such that said rows and columns thereof are substantially aligned to said columns and rows of said preceding switch array.

54. A method of demultiplexing a collimated wavelength-multiplexed beam and switching individual wavelength components thereof to respective output ports, comprising the steps of:

(a) providing a wavelength separator/combiner including:

(i) a first diffraction grating including a first plurality of diffractive elements on a surface thereof, and

(ii) a second diffraction grating including a second plurality of diffractive elements on a surface thereof that is parallel to and offset from said surface of said first diffraction grating;

(b) directing the beam at said surface of said first diffraction grating, thereby separating the beam into the individual wavelength components ,

(c) introducing the components into the switch array complex of claim 52, and

(d) switching the components to respective output ports thereof.

55. A method of multiplexing a plurality of individual wavelength rays into a single beam comprising the steps of:

(a) providing a wavelength separator/combiner including:

(i) a first diffraction grating including a first plurality of diffractive elements on a surface thereof, and

(ii) a second diffraction grating including a second plurality of diffractive elements on a surface thereof that is parallel to and offset from said surface of said first diffraction grating;

(b) introducing the individual wavelength rays into respective input ports of the switch array of claim 52;

(c) switching said rays, in a suitable alignment for combining said rays into a single multiplexed beam in said wavelength recombiner; and

(d) directing said rays, so aligned, at said surface of said first diffraction grating, thereby combining said rays into said single multiplexed beam.

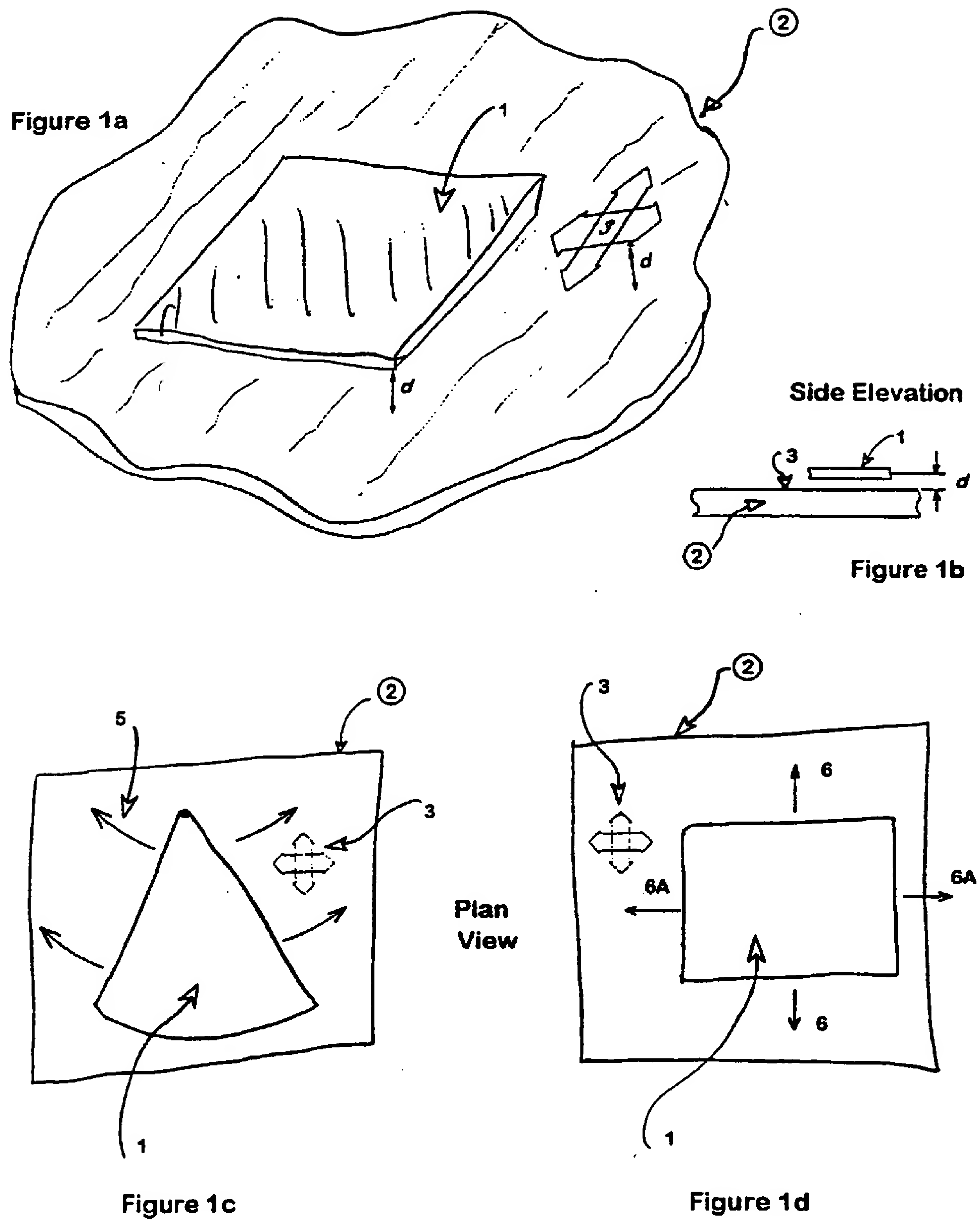


Figure 1a
2
1
3
d
d
Side Elevation
1
3
d
2
Figure 1b
5
2
3
1
Figure 1c
Plan
View
3
2
6
6A
6A
6
1
Figure 1d

Figure 1

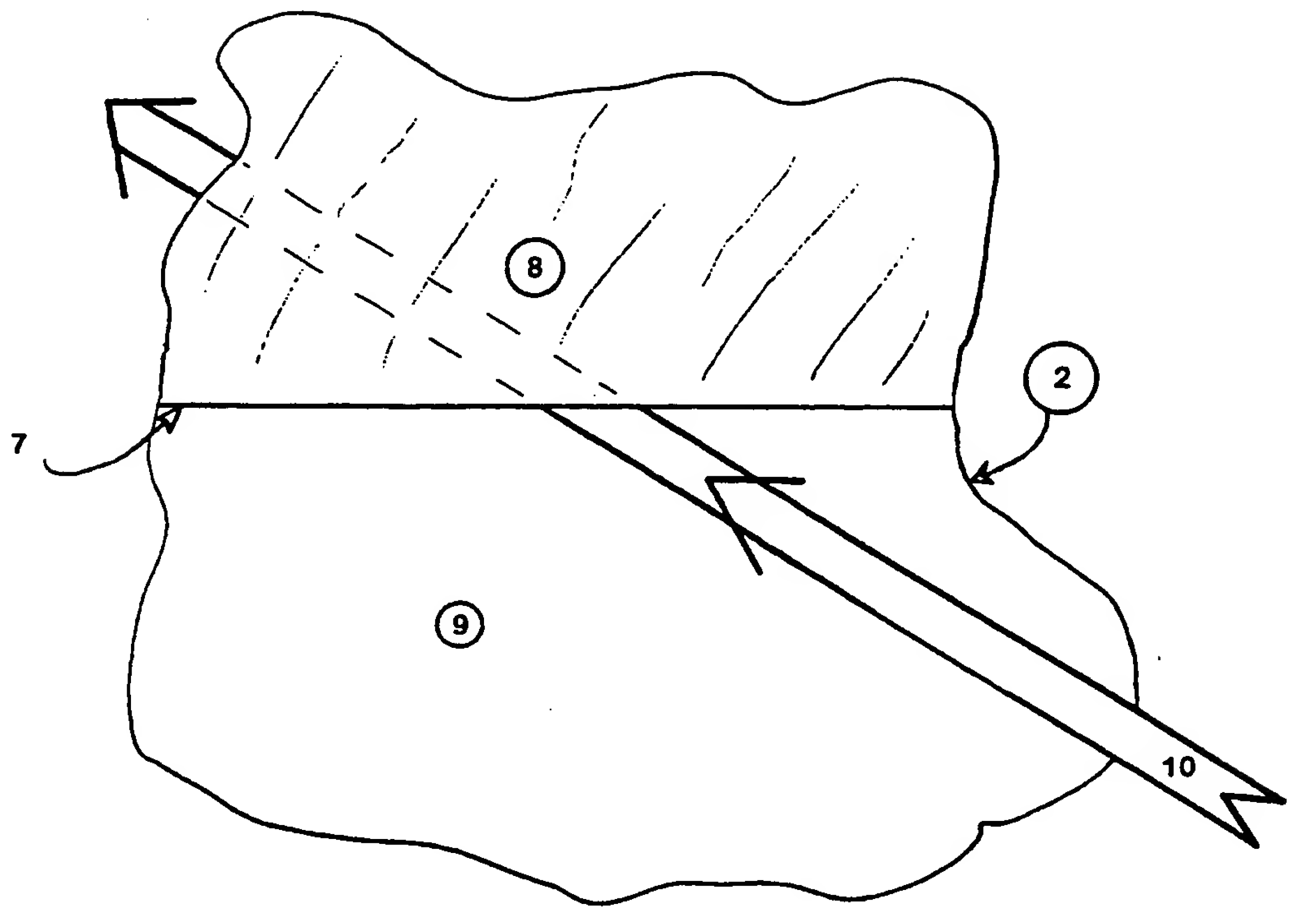


Figure 2

Side Elevation

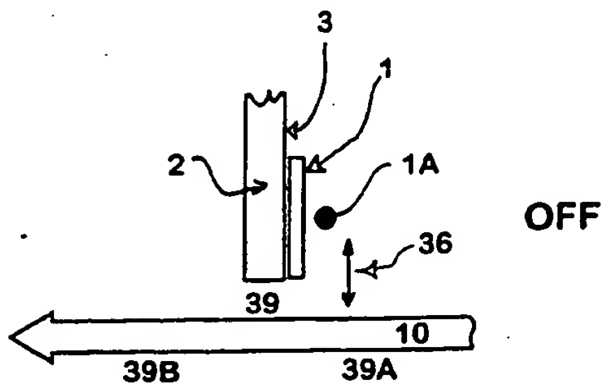


Figure 3a

Plan View

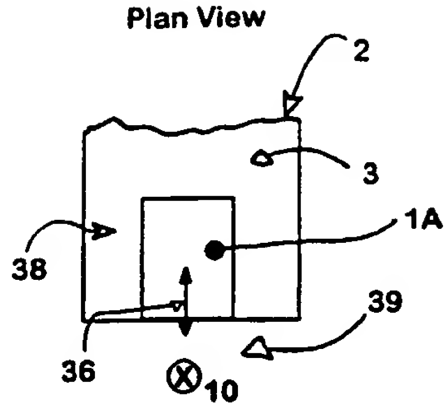


Figure 3b

Side Elevation

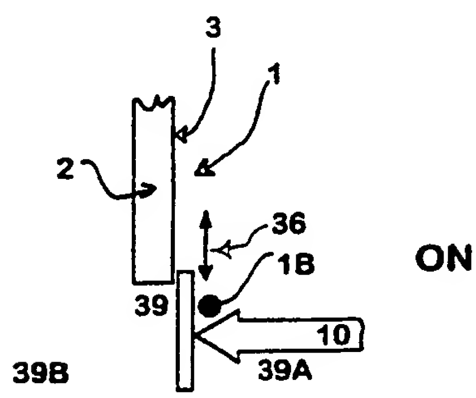


Figure 3c

Plan View

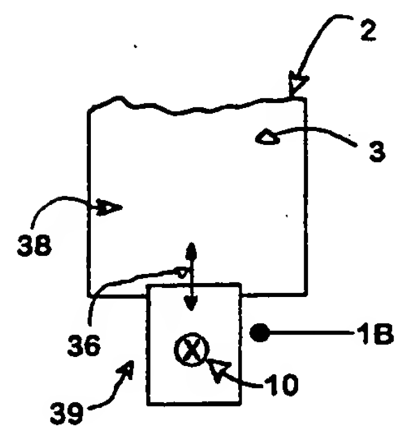


Figure 3d

Side Elevation

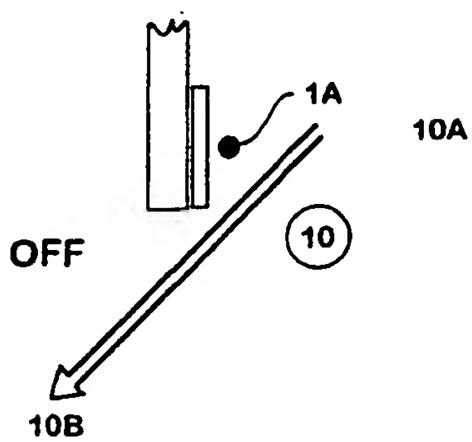


Figure 3e

Side Elevation

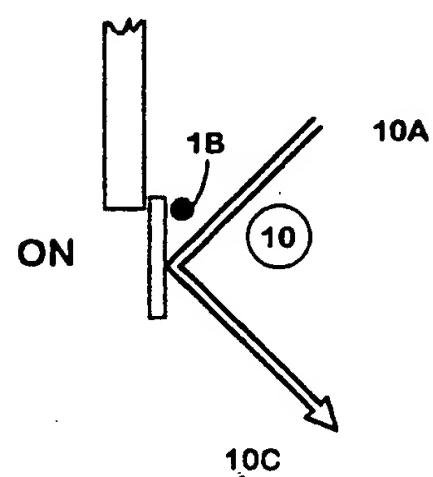


Figure 3f

Figure 3

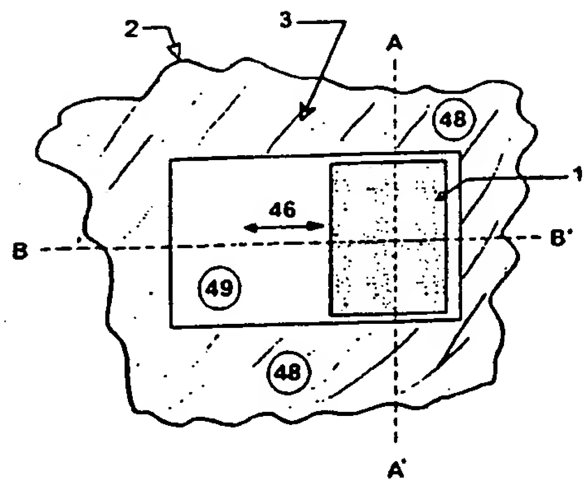


Figure 4a

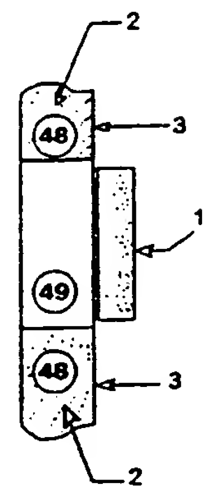


Figure 4b

Section B — B'

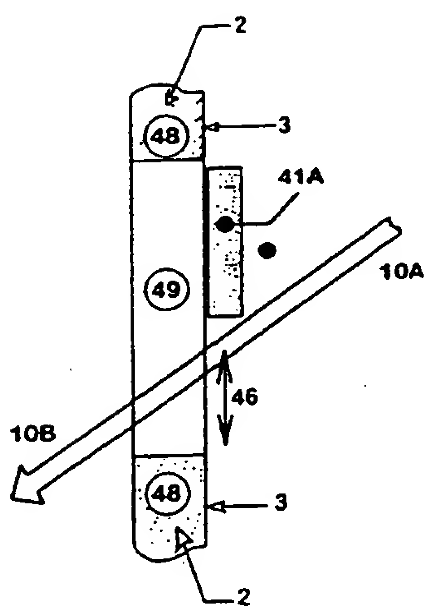


Figure 4c

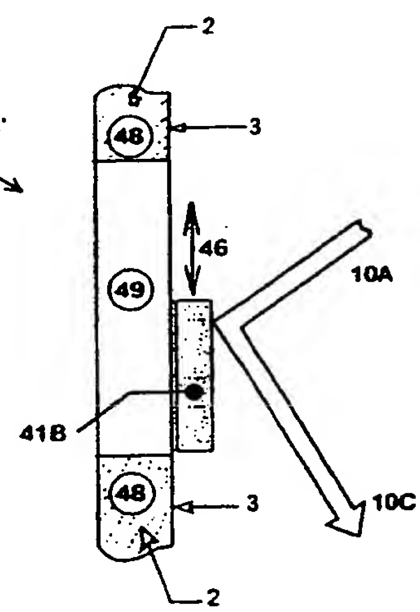


Figure 4d

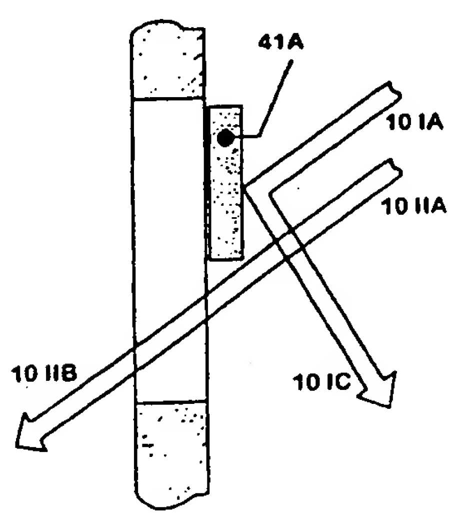


Figure 4e

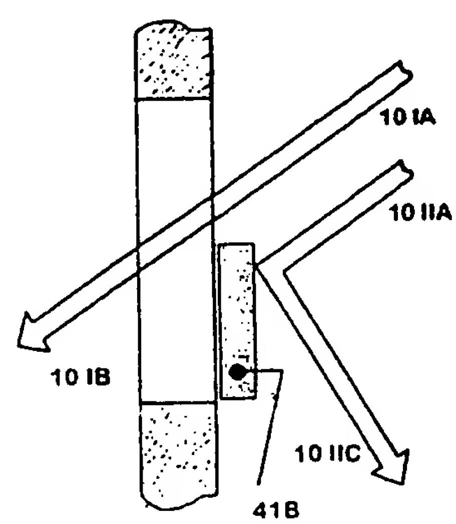


Figure 4f

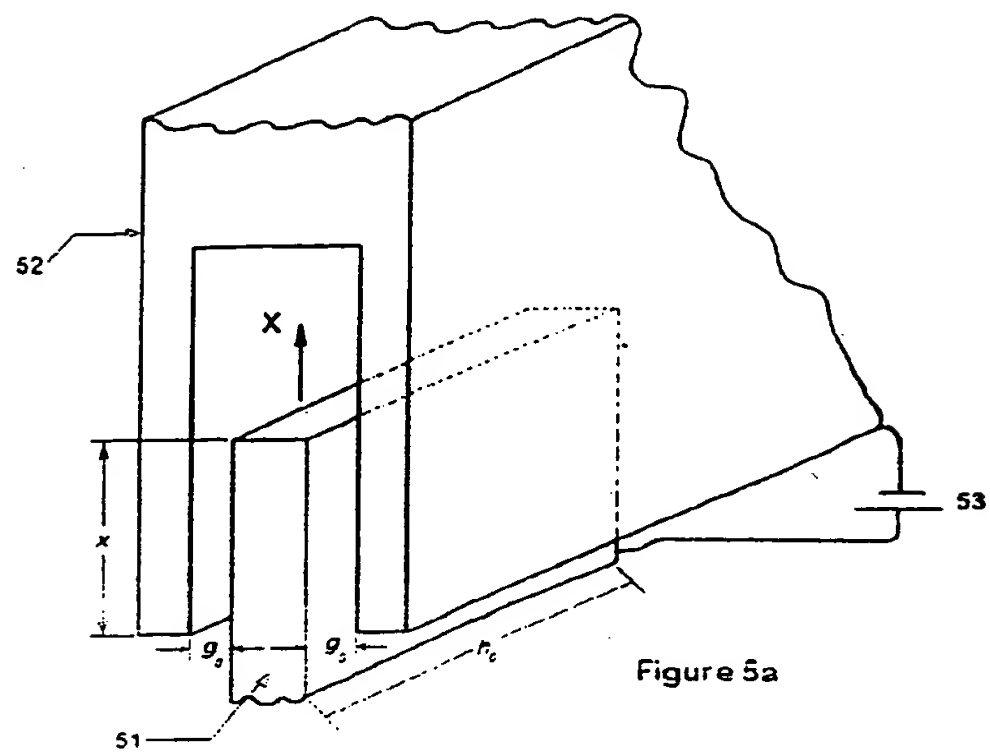


Figure 5a

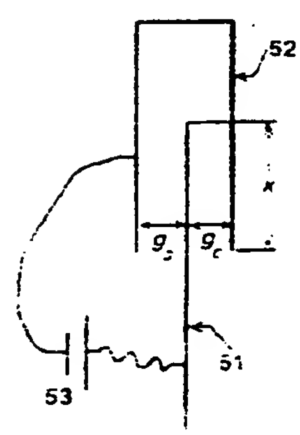


Figure 5b

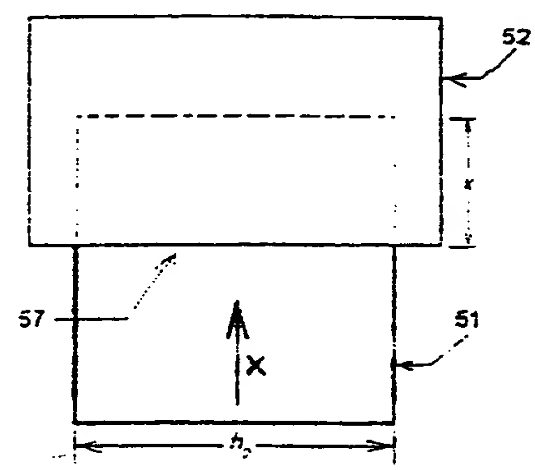


Figure 5c

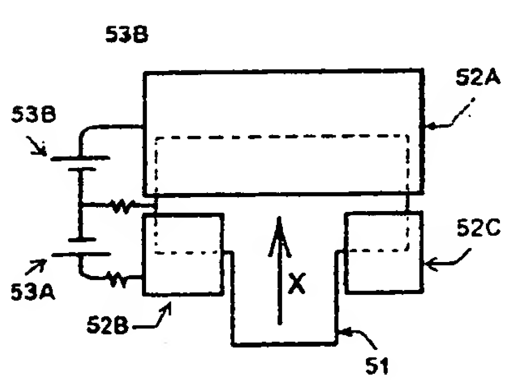


Figure 5d

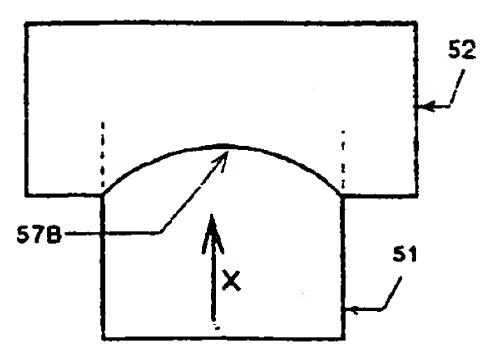
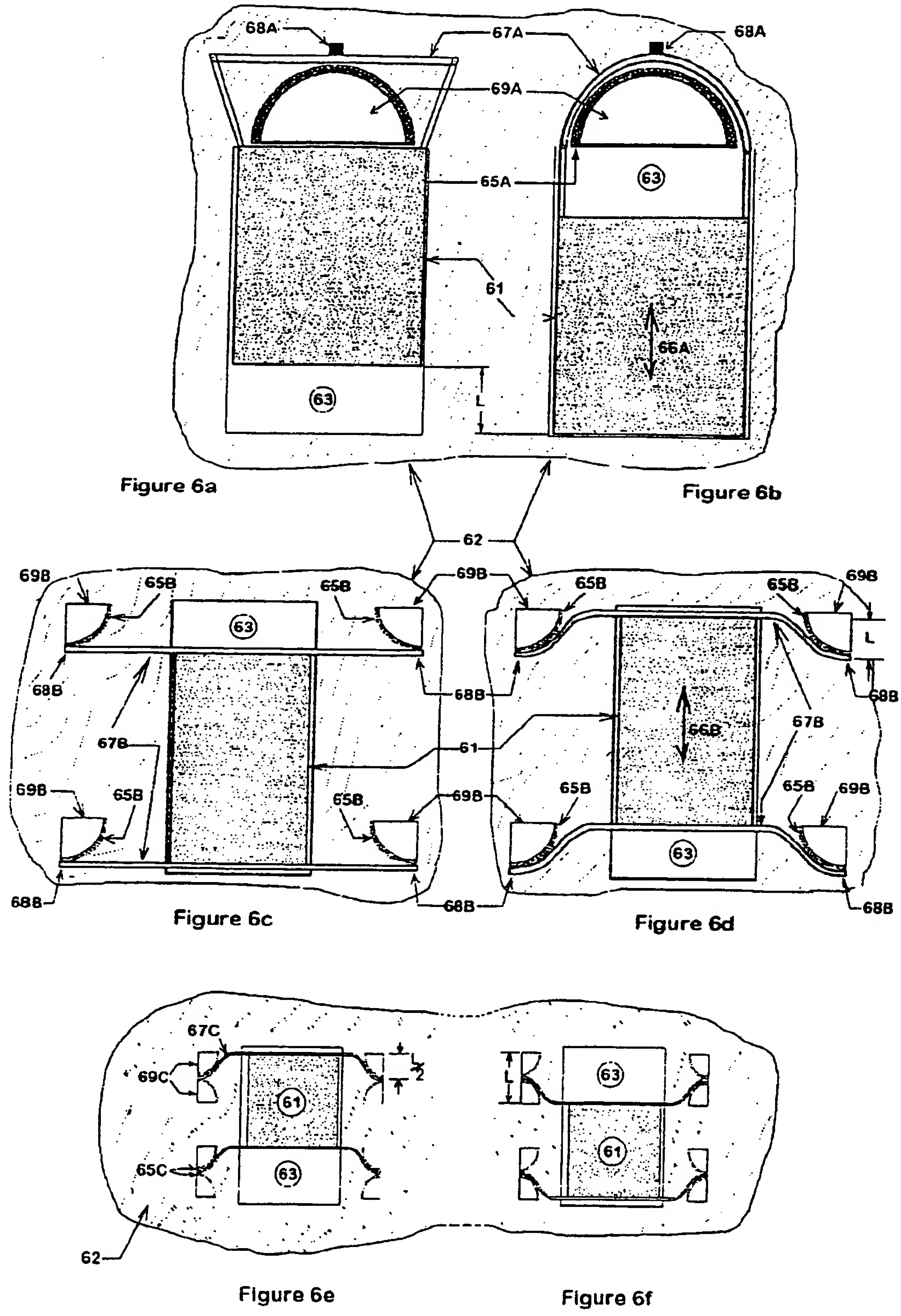


Figure 5e

Figure 5


68A
67A
68A
69A
65A
63
61
66A
L
63
Figure 6a
Figure 6b
62
69B
65B
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69B
69B
65B
65B
69B
63
68B
68B
L
68B
67B
66B
67B
61
69B
65B
65B
69B
65B
65B
69B
63
68B
68B
68B
Figure 6c
Figure 6d
67C
69C
L/2
L
63
61
61
65C
63
62
Figure 6e
Figure 6f

Figure 6

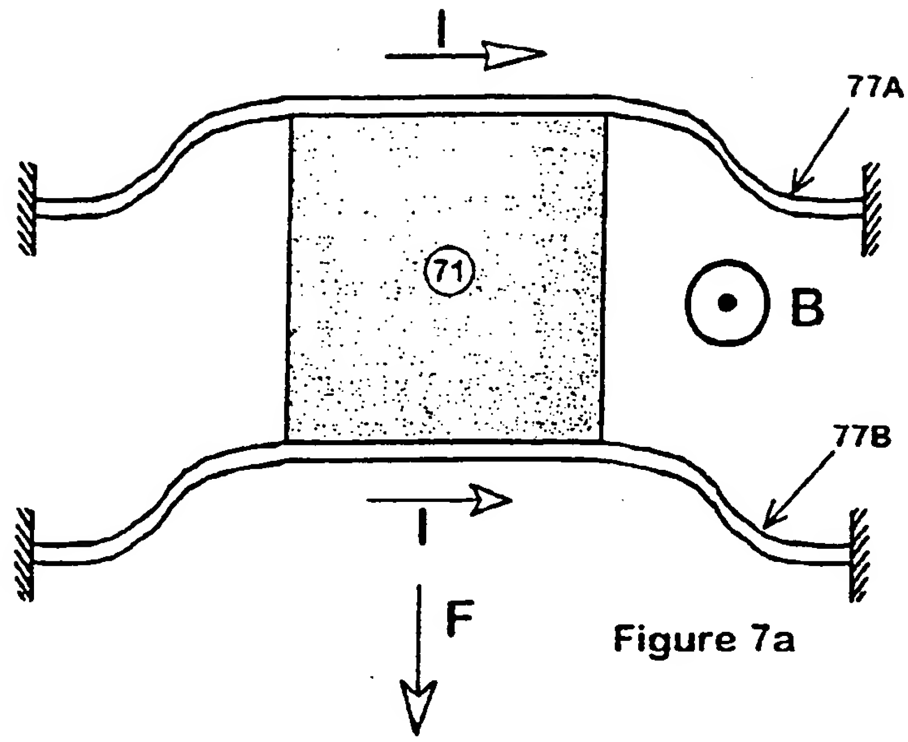


Figure 7a

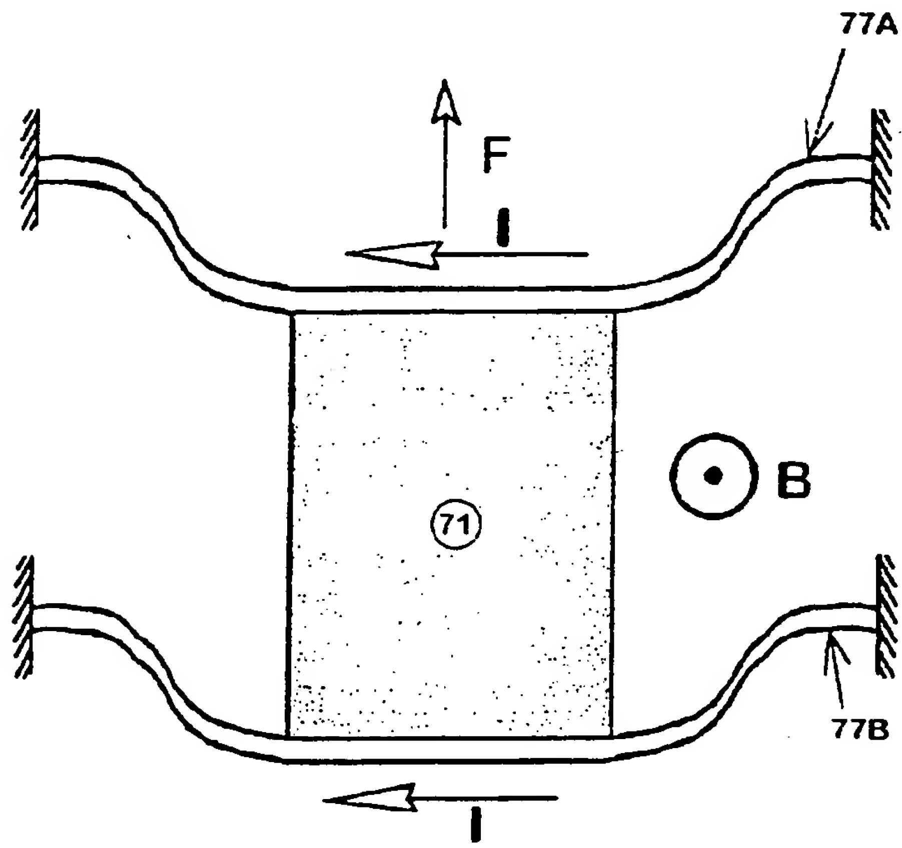
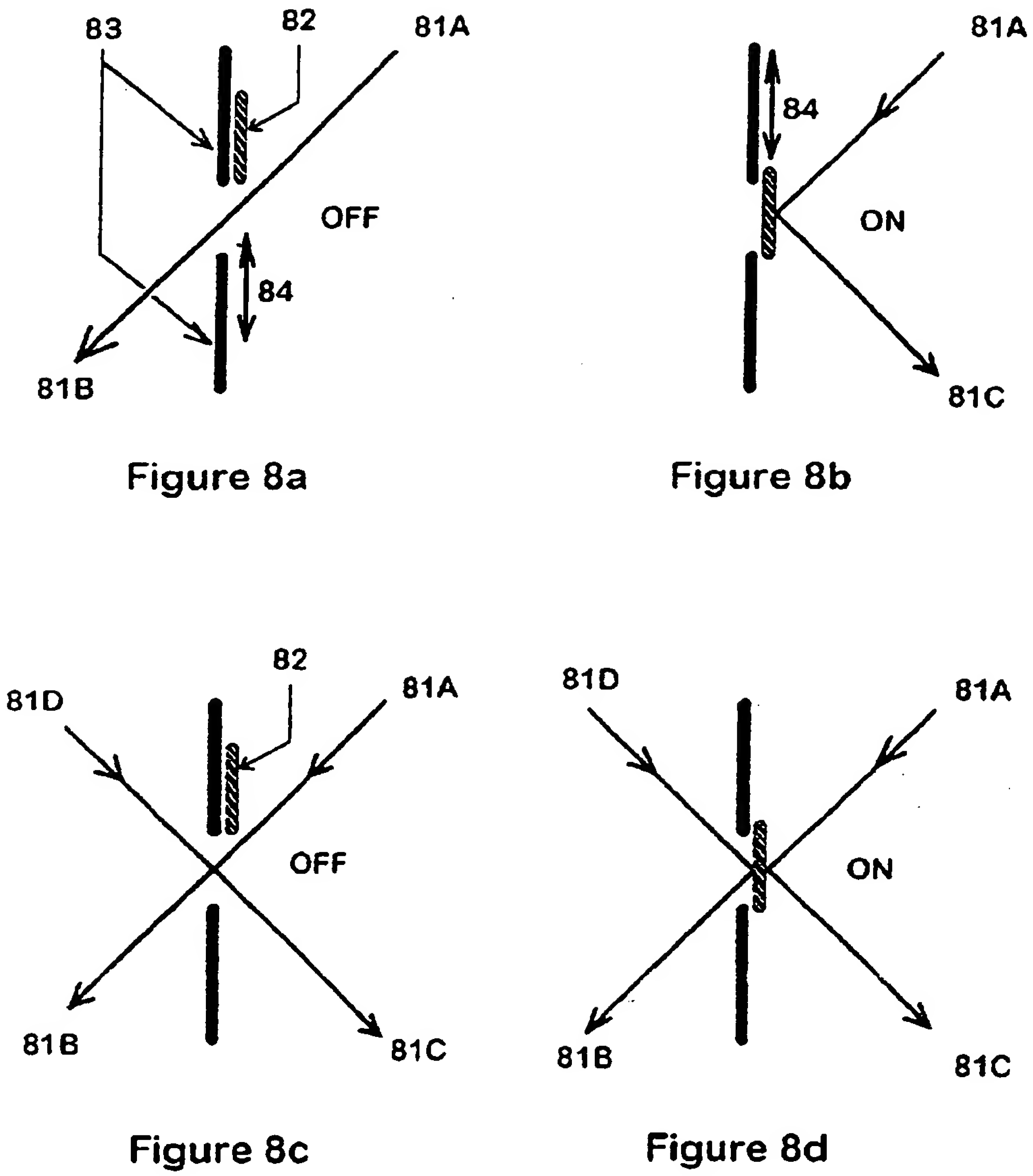


Figure 7b

Figure 7


83
82
81A
OFF
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81B
Figure 8a
81A
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81C
Figure 8b
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81C
Figure 8c
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81A
ON
81B
81C
Figure 8d

Figure 8

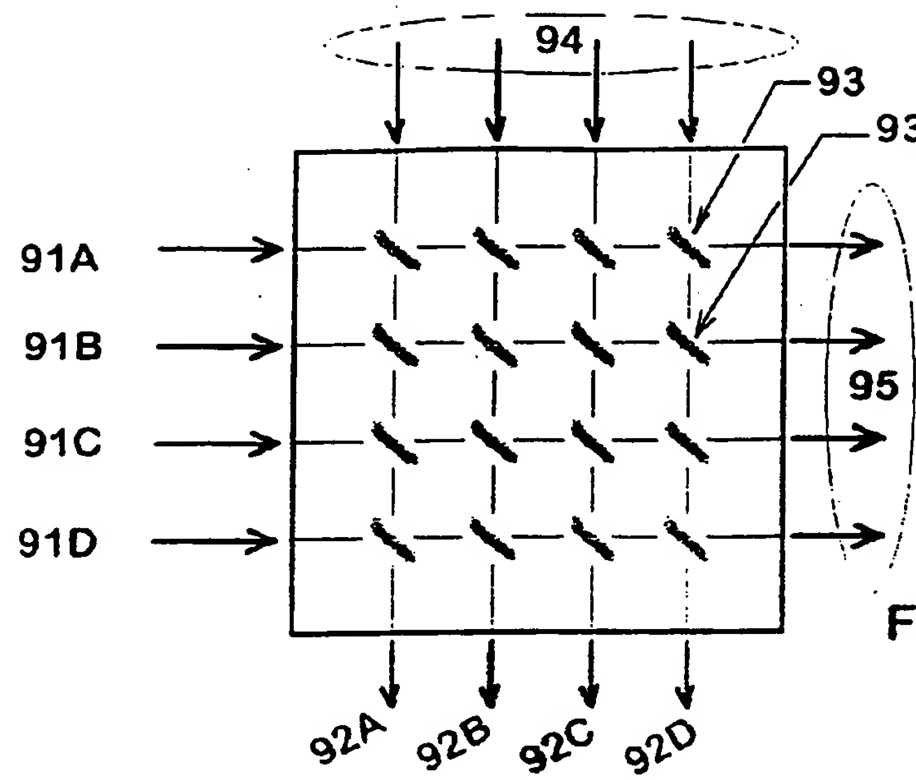


Figure 9a

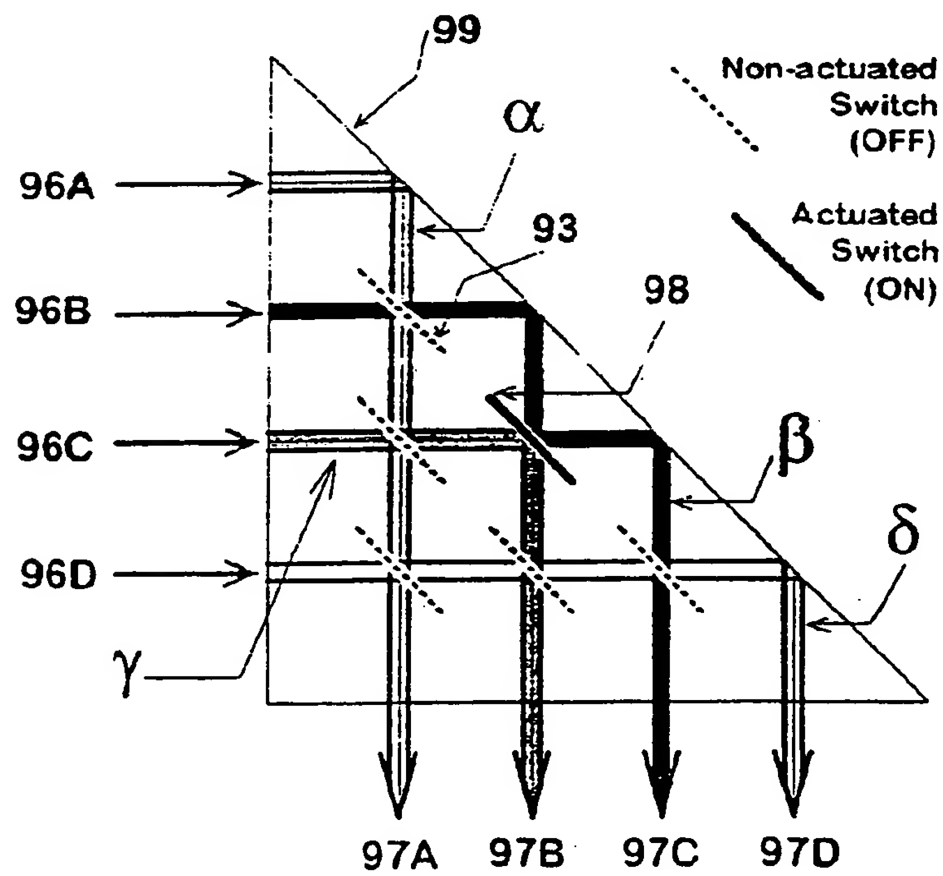


Figure 9b

Figure 9

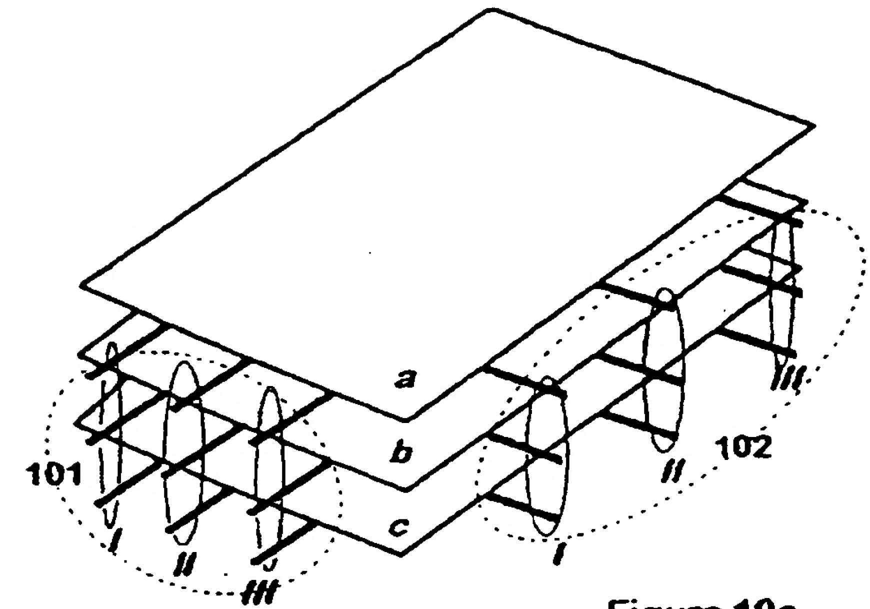


Figure 10a

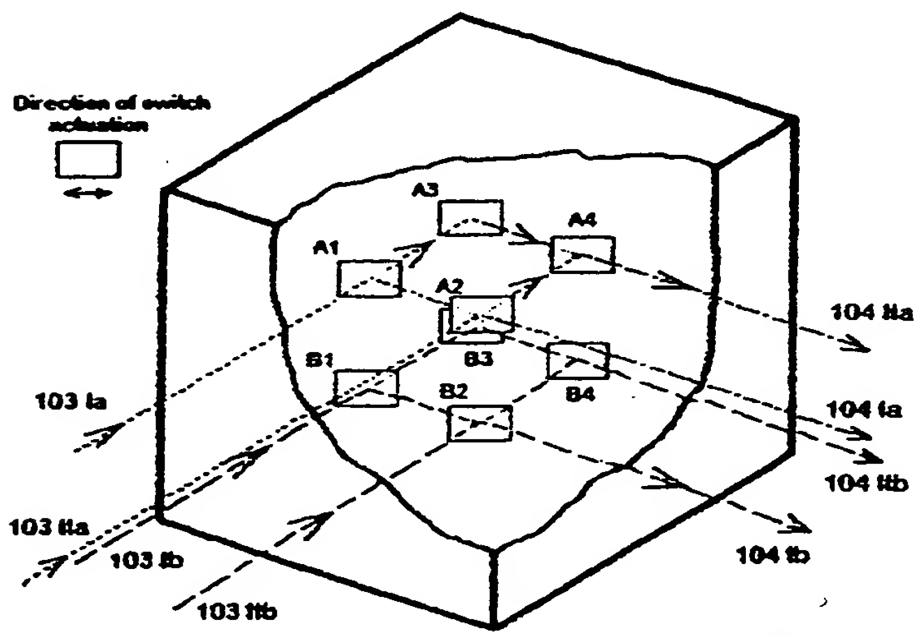


Figure 10b

Figure 10

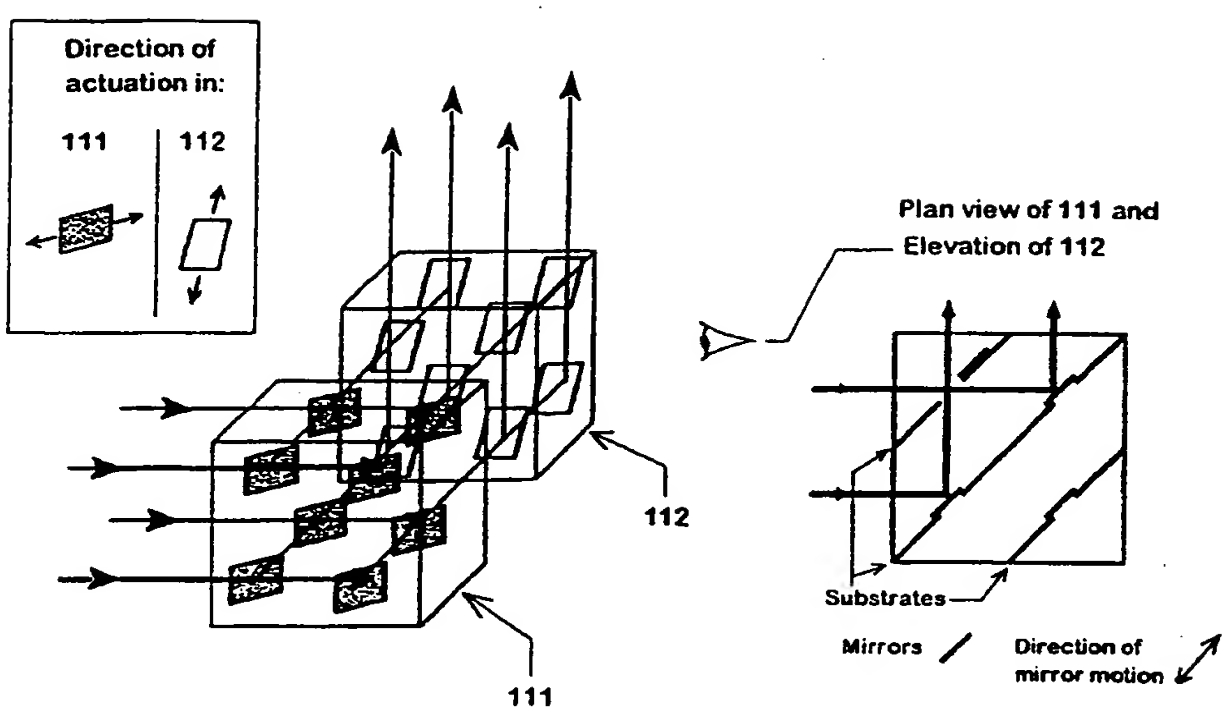

Direction of
actuation in:
111
112
Plan view of 111 and
Elevation of 112
112
111
Substrates
Mirrors
Direction of
mirror motion

Figure 11a

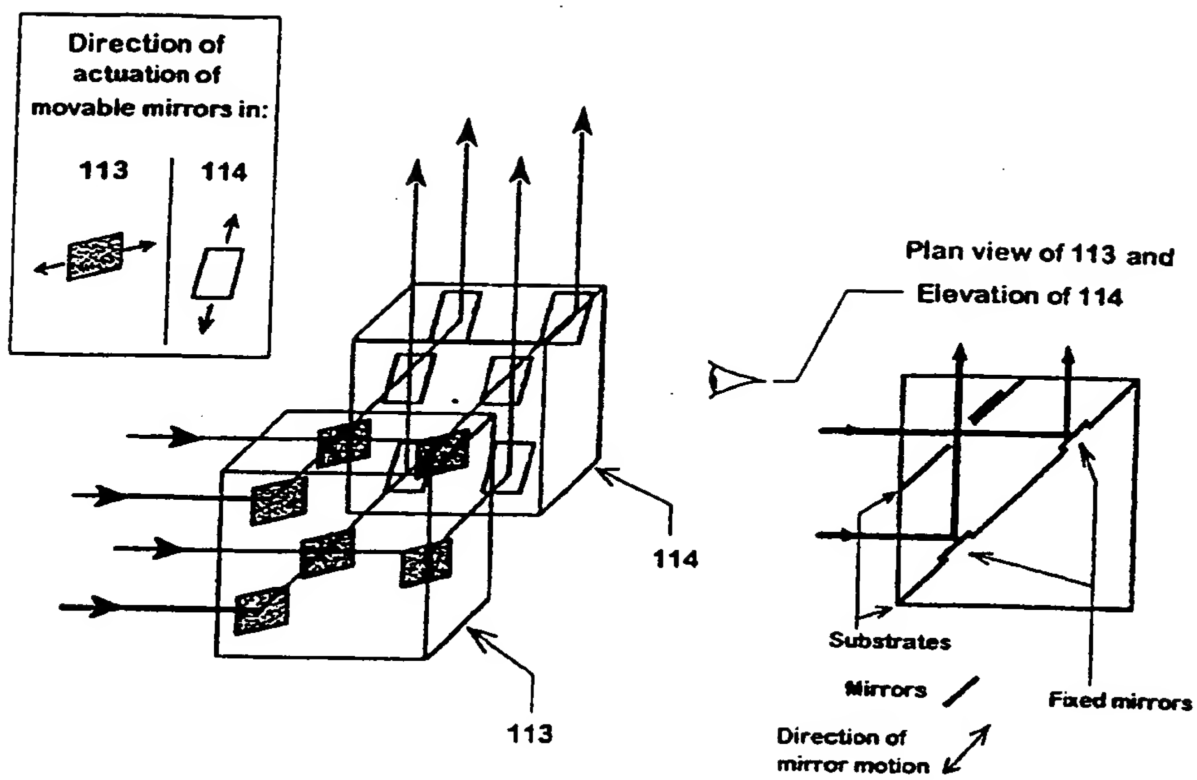
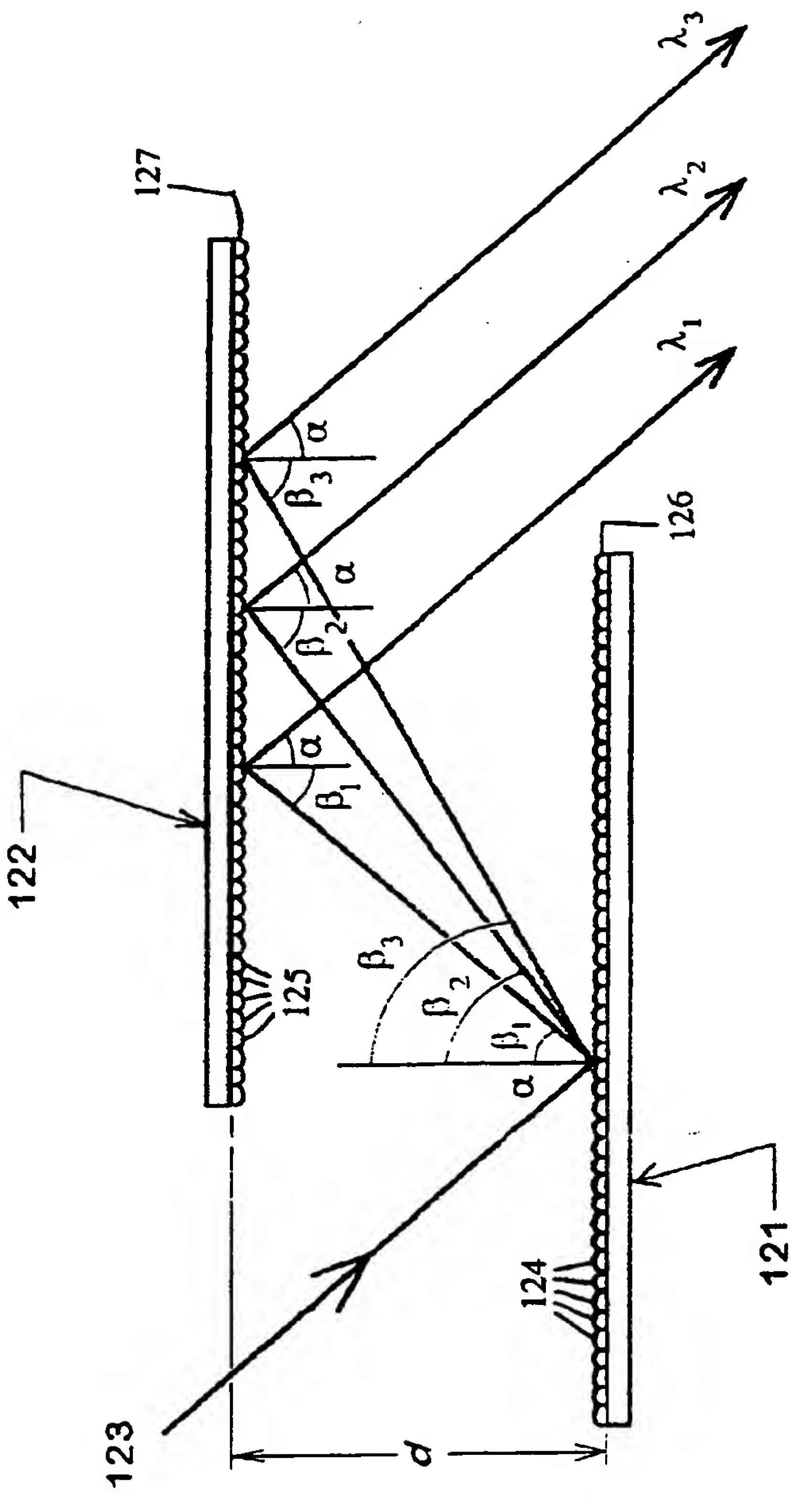

Direction of
actuation of
movable mirrors in:
113
114
Plan view of 113 and
Elevation of 114
114
113
Substrates
Mirrors
Fixed mirrors
Direction of
mirror motion

Figure 11b



127
122
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d
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121
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λ_1
λ_2
λ_3
α
β_1
β_2
β_3

Figure 12

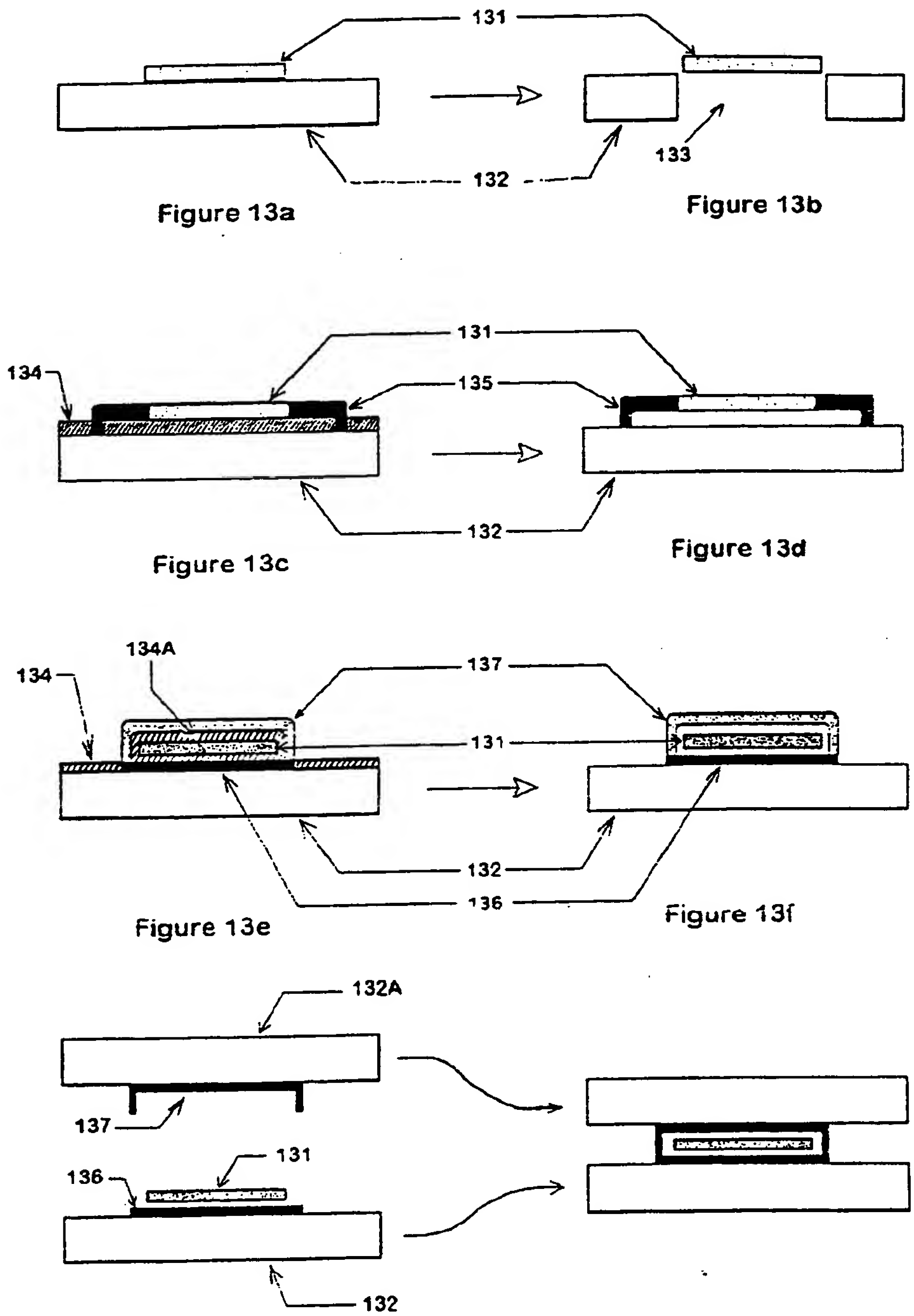

Figure 13a

Figure 13b

Figure 13c

Figure 13d

Figure 13e

Figure 13f

Figure 13g

Figure 13h

Figure 13

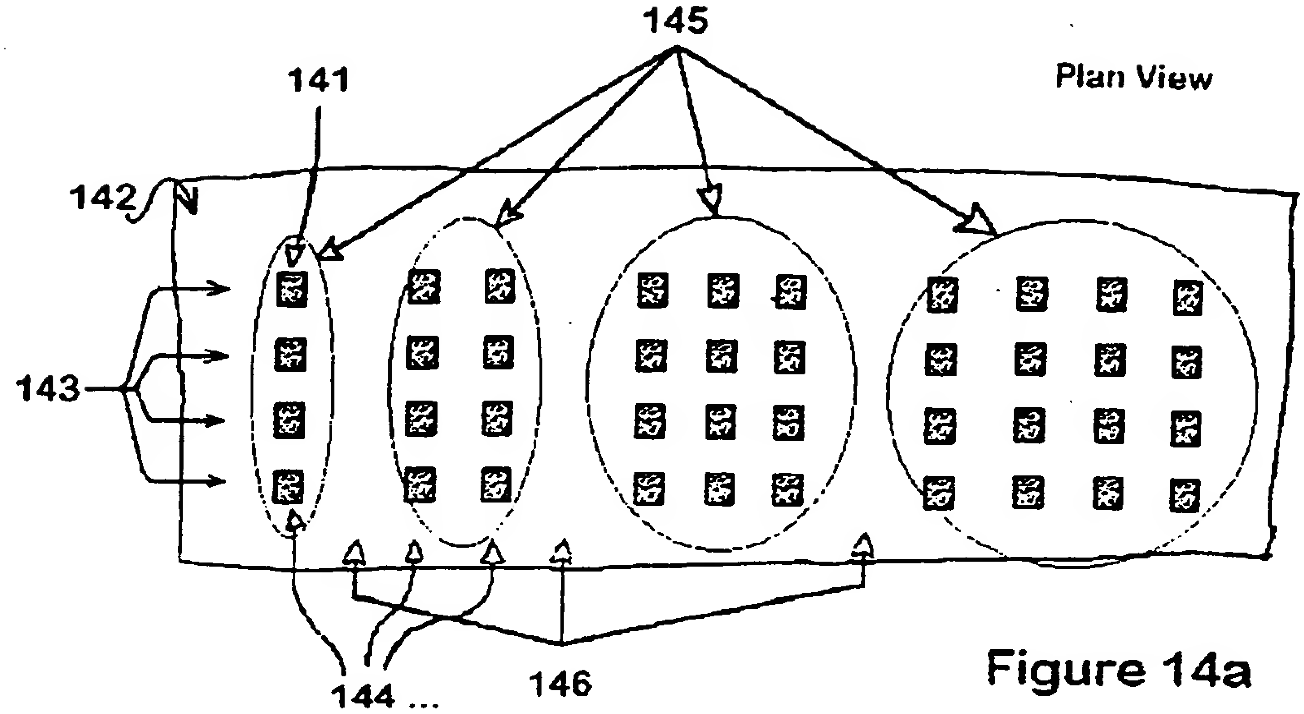

Figure 14a

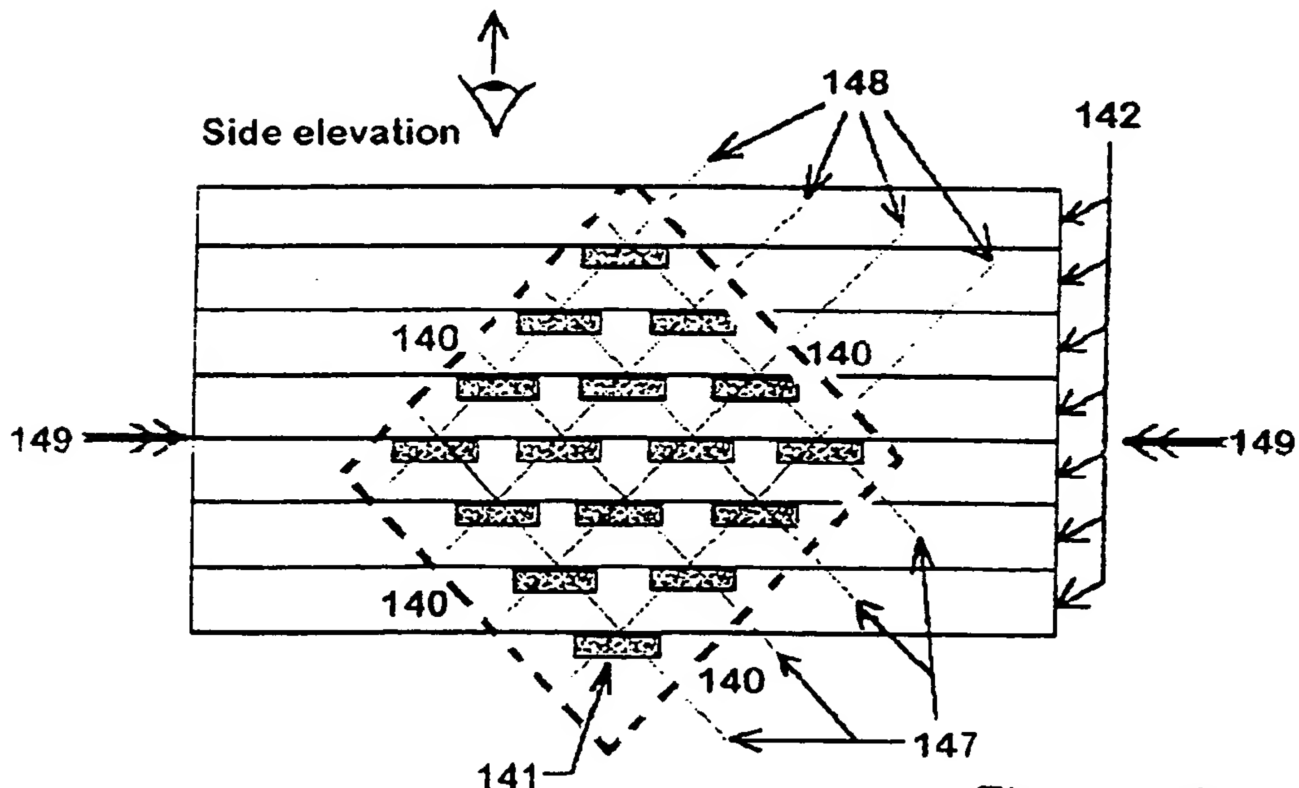

Figure 14b

Figure 14